Private LTE/5G 2019

Abstract: This report provides a global view of the Private LTE market including infrastructure and devices. The report also identifies the market by industry sector and cellular technology generations offering a glimpse of how 5G uptake will impact the market. It also highlights cellular penetration in the context of the overall private wireless market.

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MOBILE EXPERTS

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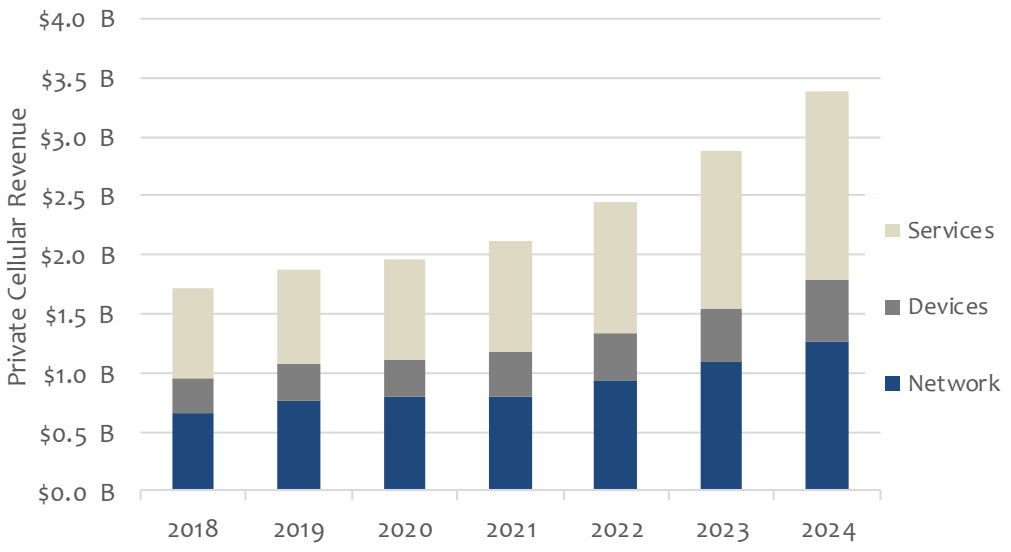
1 EXECUTIVE SUMMARY

Driven by the need for reliable, secure, and predictable connectivity, several large industry verticals, including Mining, Oil & Gas, Utility, Government, Manufacturing, and others, are considering "Private LTE" (or more broadly Private Cellular including 5G) as they undertake digital transformation projects. Private LTE offers some key benefits especially in wide-area coverage scenarios including quality of service, reliable low-latency, security, and mobility. The global Private LTE/5G market, defined as an enterprise-managed network with dedicated equipment, is forecasted to grow at over 10% CAGR to about $3.4B in 2024. Excluding services, the Private LTE/5G equipment sales, including user and IoT devices, will grow from over $960M in 2018 to about $1.8B in 2024.



Source: Mobile Experts

Chart 1: Private Cellular Revenue Forecast, 2018-2024

The size of Private LTE/5G market differs widely across industry verticals. The Government sector, which includes Public Safety and Military applications, and the Transportation sector, which includes airports, shipping ports, and railway, make up a big share of today's Private LTE market as the industrial applications require very large coverage areas. Meanwhile, Mobile Experts forecasts very fast growth in Manufacturing (over 100% CAGR albeit from a very small base) and Mining (over 50% CAGR) driven by industrial IoT and full autonomy use cases. The industrial automation driven by IoT sensors and analytics will highlight the requirement for deterministic wireless connectivity that Private LTE and 5G provide.

The majority of Private LTE equipment market will be based on LTE as most industrial applications can be handled with LTE mobile broadband features. As the 5G URLLC features in 3GPP Release 16 come available in solutions, we expect 5G to take an increasing share of

the "Private LTE" especially as factory automation in Manufacturing and full autonomy use cases in Mining proliferate. As the 5G ecosystem scales beyond our forecast period, we expect 5G to become the dominant technology choice in many "Private LTE" deployments.

The Private LTE/5G ecosystem is coming together just as industry verticals are seeking new connectivity platforms to handle more complex industrial automation with sensors and analytics. Small cells with virtualized core networks offer a self-contained solution that enterprises can deploy locally. Meanwhile, enterprises have more spectrum bands to consider for Private LTE systems whether that's CBRS shared spectrum in the USA, 3.7-3.8 GHz "local" frequency dedicated for industrial use in Germany, or 3.8-4.2 GHz shared spectrum in the UK. Also, the MulteFire Alliance is looking to broaden LTE use in an unlicensed spectrum ranging from 800/900 MHz band for NB-IoT to 2.4 and 5 GHz unlicensed band for mobile broadband. Challenges remain in spectrum access and business models, but it looks like pieces are falling into place at this early stage.

2 PRIVATE NETWORKING TRENDS ACROSS INDUSTRY

Private, or enterprise, networking has been a staple of IT departments at many organizations for decades. While we mostly think of IP/ethernet local area networking and WLAN as the dominant form of private networking, there is a multitude of wireless and wired network solutions that serve different industry verticals. A fundamental driver of communication network investments across the different industry sectors centers on productivity and operational efficiency through modernization of communication networks, end devices, and applications that facilitate how people communicate with each other and with machines and sensors. A complex array of machines and applications in IT environments, and increasingly in the field environments demand a fast, reliable, and secure network environment.

Oil & Gas

The Oil & Gas (O&G) industry is highly dependent on commodity prices. The industry went through a digital transformation about 4-5 years ago when the commodity price took a nosedive. The O&G companies were forced to efficiently utilize existing oil fields for higher production as money for expensive exploration dried up.

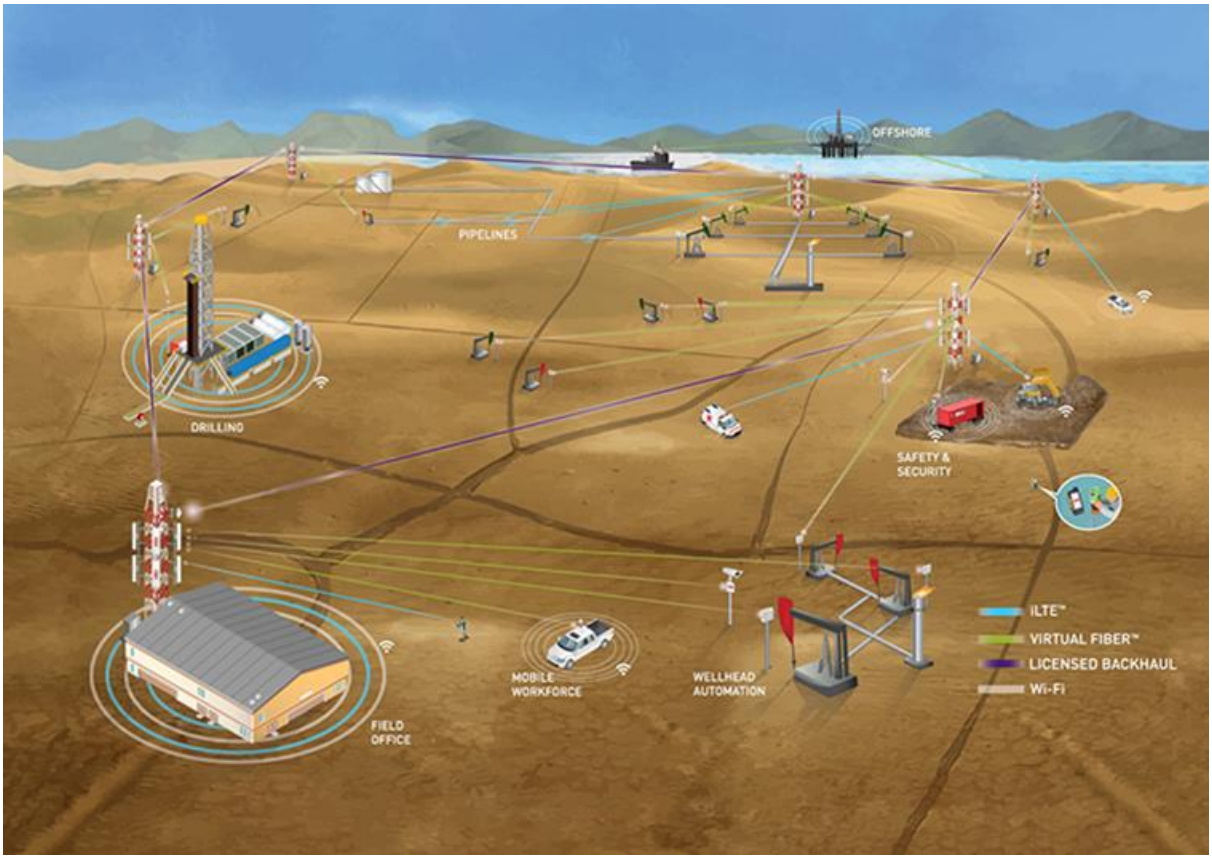
Source: businessinsider.com

Figure 1. WTI Oil commodity price (5-year view)

According to PwC consultancy, the global O&G capital expenditure dropped 44% from 2014 to 2016.[1] While we expect the industry capital expenditure to grow steadily in mid-single digits in the near term, it is hard to predict when the next pricing "shock" will occur and impact O&G operators' capital spending. Based on historical commodity pricing trends, we believe an upward trend is more likely than down at this stage. Whether the overall capital expenditure (i.e., $400-500B for the industry) goes up or down each year, it is generally

[1] PwC 2018 Oil and Gas Trends 2018-19

acknowledged that IP network transformation, including private wireless networking, is becoming increasingly important for O&G operators as real-time, reliable, and secure networking is becoming critical for the automation of the entire process from production, distribution, and refinement of oil.



Source: Redline Communications

Figure 2. Private Wireless Network in Oil Fields

As illustrated above, an oil field can be onshore or offshore. Private wireless networking is especially important for offshore facilities such as thousands of oil platforms found in the Gulf of Mexico and the North Sea because it eliminates cable-free installation which is especially useful in places where cabling is not an option – like in the middle of the sea. On onshore oil fields, a private wireless network provides redundancy to wired data networks along hundreds of kilometers of oil or gas pipeline. Close monitoring of oil/gas pipeline along with pumping or compression stations is important to ensure the integrity of the distribution flow. At a refinery, a private wireless network is important to continuously monitor the refining process through the reading of numerous sensor data and feeding that to analytics and management systems that ensure that the process values are within KPIs.

Mining

Compared to the Oil & Gas industry, the mining industry is undergoing a digital transformation towards IP networking now. While various proprietary wireless technologies have provided traditional M2M readings of sensors and long-range data transmission links, several key factors are driving the industry towards IP networking and private LTE and 5G more specifically. First and foremost, the industry is moving towards full autonomy in which remote field operations are managed at regional or central office many miles away. For example, Rio Tinto has been running remote-controlled drills, dozers, and driverless hauling trucks at a surface mine in Australia and is now looking to expand the autonomous operation to its other mines. The company's drive for autonomy is yielding positive outcomes besides the safety factor of not having to have people work around these massive machines in a typical mine. According to a Rio Tinto executive, the driverless trucks are about 15% cheaper to run than vehicles with a driver behind the wheel. (It is interesting to note that Komatsu whose trucks are used in Rio Tinto mines recently announced that its FrontRunner autonomous haulage system has been qualified to run on private LTE networks, marking the industry's first autonomous truck for private LTE.)

Source: MIT Technology Review

Figure 3. Autonomous hauling trucks at a mine

Of course, the full autonomy requires real-time and predictable wireless network infrastructure that can connect people and machines on the move which is where cellular LTE shines. Another key driver of Private LTE in mining is the increasing demand for real-time analytics, asset tracking, and video surveillance is exerting greater demand on network infrastructure that can provide reliable and secure data capacity and scale with ease.

Private cellular networks are becoming favored in mining as Wi-Fi, and other proprietary solutions are struggling to keep pace operating in harsh environments like in mining. In the past, mining communications mostly involved voice dispatching. Then, SCADA systems were introduced in hub-and-spoke architecture to transmit terminals data back to centralized servers in a hub. As "mobile" applications such as remote-controlled hauling trucks and drills are employed in full autonomy operations, network requirements are becoming more demanding – towards real-time, reliability, predictability, and security. While the traditional M2M communication leveraging IPsec tunnels on Wi-Fi meshing architecture can certainly take on the task, the tunneling and meshing introduce inefficiencies that impede the goals of full autonomy that requires real-time response.

Lastly, mining companies are looking to consolidate different network types into one single network that can provide voice and data services as well as handle more IoT applications. Consolidation improves OPEX, and that's another goal that is prompting major miners to adopt LTE for the problems that it solves. LTE and 5G offer a long-term technology roadmap with robust supplier ecosystem that major mining companies are willing to invest for a long haul.

Utilities

Utility companies have a very long-term view of network lifecycle. Whereas mobile operators typically make network technology upgrades every 8-10 years, Utility companies think of a major network technology upgrade every 20-30 years. Utilities have leveraged wired and wireless technologies to piece together telecommunications networks that support a variety of functional elements in a field area including substation automation (e.g., voltage regulators, breaker controllers), distribution automation devices (e.g., capacitor banks, reclosers), AMI collectors and meters, and sometimes connectivity to remote substations. The below figure depicts a utility communications network overlaid on top of an electricity distribution system.

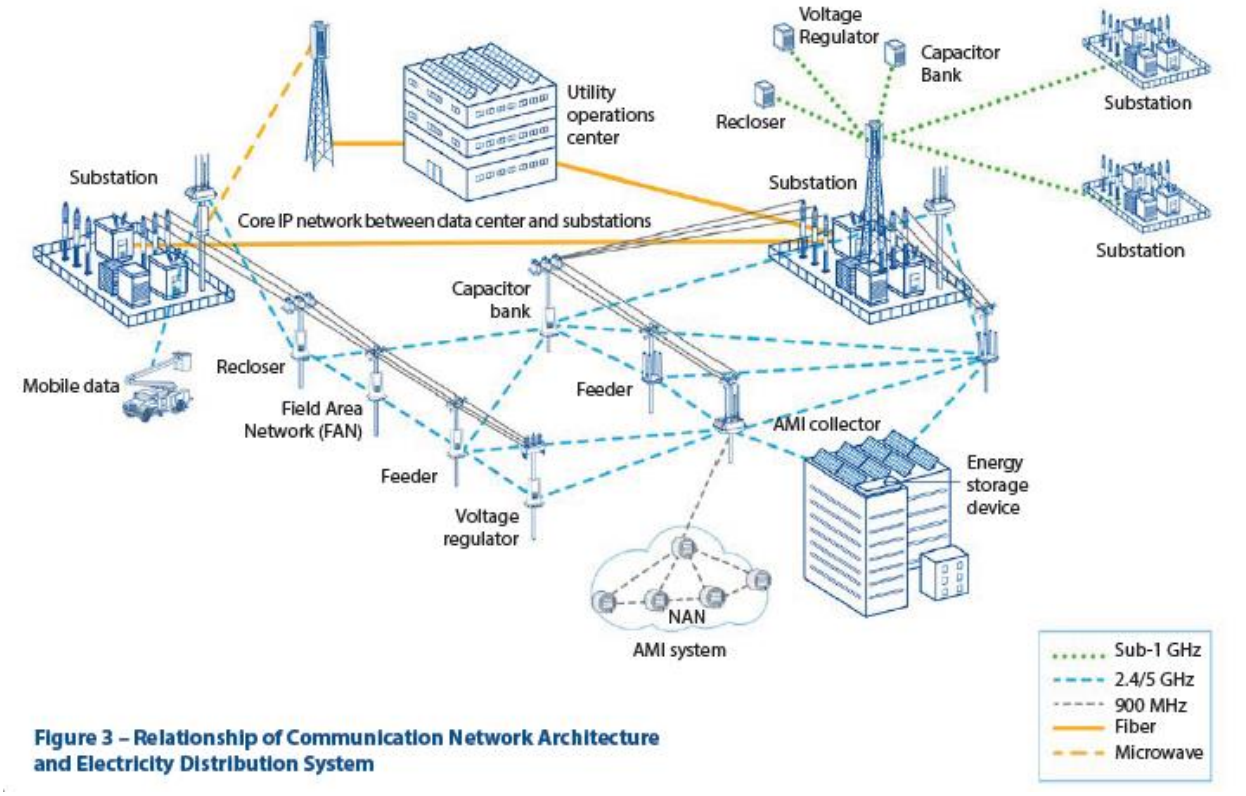


Figure 3 – Relationship of Communication Network Architecture and Electricity Distribution System

Source: ABB article on electricity-today.com

Figure 4. Utility Communications Network on Electricity Distribution

As shown above, the field area network covering the *Distribution* portion of a Utility network is comprised of various wireless technologies ranging from narrowband meshing (on 900 MHz) for AMI metering to broadband Wi-Fi meshing (on 2.4 and 5 GHz) to connect various automation devices and a combination of fiber and point-to-point microwave for Core IP network to connect operations center to substations.

Many 900 MHz links known as Multiple Address System (MAS) radios[2] were put in place back in the 1990s utilizing the 900 MHz (928-929 MHz and 952-953 MHz) band for SCADA connectivity to remote sites. Today, it is increasingly difficult to find suppliers for this aging infrastructure. Because of the spectrum limitation and FCC's ongoing effort to "narrow banding" initiative[3] to drive more efficient use of spectrum, the Utility industry is seeking new spectrum options for a wireless network upgrade. For the US market, Utilities are exploring the 4.9 GHz public safety (4940-4990 MHz) band. Meanwhile, some European Utility companies appear to be evaluating the possibility of leveraging the 400/450 MHz spectrum for wireless IP connectivity.

[2] MAS system consists of a master radio that communicates with multiple remote radios on paired (up/down) frequencies in the 900 MHz band. 5W master and 1W remote radios along with directional antennas provide a long range (typically about 10 miles) with ~5 kbps data speeds (using FSK modulation).

[3] FCC requires new MAS licenses to use 12.5 kHz channels. FCC initially allocated 25 kHz channels back in the 1980's.

Utilities have traditionally used narrowband and wireless mesh networks to extend coverage, but the increasing demand for higher capacity data connections is driving Utilities to consider cellular broadband systems that offer long-term technology roadmap and a robust ecosystem of suppliers that will last. As part of the migration towards a new wireless broadband system, Utilities are seeking new spectrum band opportunities, possibly in the 4.9 GHz public safety spectrum in the USA or even possibly the 450MHz spectrum in Europe. The focus will be on the spectrum which allows the utility to own the key radio infrastructure. In other cases, depending on availability of viable spectrum and pricing of mobile operators' cellular IoT (NB-IoT or Cat-M) offerings, Mobile Experts believes that some (generally smaller) Utility companies may simply tap the "public" LTE network for network services that are closer to end consumers, such as AMI metering and certain aspects of distribution automation, rather than building out their own private cellular infrastructure. This decision will be based on a long-term ROI calculation of build vs. buy.

Utilities generally favor owning the private wireless network infrastructure as they have a long view of expensing capital investments. As they look to invest in new energy generation sources like wind farms and solar farms, they will be inclined to invest in the private wireless network to automate the energy generation sites (e.g., monitoring wind turbines for predictive maintenance). Mobile Experts expects some Utility companies to invest in Private LTE networks for the *Generation* side of the value chain as well as traditional investments in the *Distribution* segment.

Transportation

Operations at major transportation hubs like airports and shipping ports are often mentioned in the context of Private LTE. At airports, Wi-Fi is commonly used for broadband use by passengers and airport operations. In major airports, this system is overlaid with a separate cellular in-building systems like DAS for general wireless broadband connectivity and another LMR system for public safety communications. This shared environment can be costly to maintain for the airports. With the growing demand for better wireless connectivity, some airport operators are seeking a new system that offers reliable and secure wireless connectivity to handle critical airport operations. Some airport operators are leveraging Private LTE to handle critical airport operations including aircraft diagnostic data offload, real-time updates to ground crews and mobile vehicles on the airfield. In addition, the Private LTE network can direct video surveillance streaming data directly to security personnel or operations center.

At shipping ports, many automated cranes and ground vehicles use RFID and other wireless technologies for automation. While Wi-Fi solutions have served the needs for some port operators, some are seeking new solutions that offer robust range, predictable speed, and security. Video surveillance is becoming more widely used, and reliable links that support

high-bandwidth applications like video and other critical communications are becoming more important for the port operators. Moreover, as industrial IoT becomes a bigger part of the automation process at large ports, more port operators are evaluating Private LTE and 5G URLLC features, especially for industrial automation. Examples such as the ports of Rotterdam and Qingdao are in full operation today.

Government (Public Safety, Military)

Public safety is a major use case driving Private LTE adoption in the Government sector. Public Safety LTE (PS-LTE) networks have been deployed in some countries, most notably in China and Australia, and major PS-LTE systems are being rolled out in Korea and the USA. Also, several countries have been trialing PS-LTE, and we expect some to roll out PS-LTE as governments allocate budget for this critical infrastructure. According to GSA, ten countries have deployed or in the process of launching PS-LTE. We are aware of PS-LTE launch in several major Chinese cities through Huawei's eLTE solutions.

Moreover, Australia's LANES PS-LTE network was launched via Telstra-managed network using dedicated spectrum in the 700 MHz band. Besides those, the FirstNet PS-LTE in the USA and Korea's PS-LTE systems are major nationwide systems represent major PS-LTE systems. (It should be noted that we do not consider FirstNet network investment as "Private LTE" since the dedicated spectrum and network resources are shared with AT&T consumer mobility customers. In contrast, the Korea PS-LTE is considered "Private LTE" since the dedicated spectrum and network are for the public safety use only.)

Source: ABB article on electricity-today.com

Figure 5. Public Safety and Military are leading Private LTE use cases in Government

A major driver of PS-LTE is high-capacity data connectivity that LTE offers. While the most common application on public safety systems is voice, many public agencies including police, fire department, and others are evaluating data-intensive applications such as video. Mapping, location-based services, and AR/infrared glass for firefighters are, for example,

some of the data-oriented applications that legacy systems can't support. The desire to unify disparate first-responder Land Mobile Radio (LMR) systems onto a single powerful LTE network that can be used for mission-critical communications and applications across agencies is another key driver for PS-LTE.

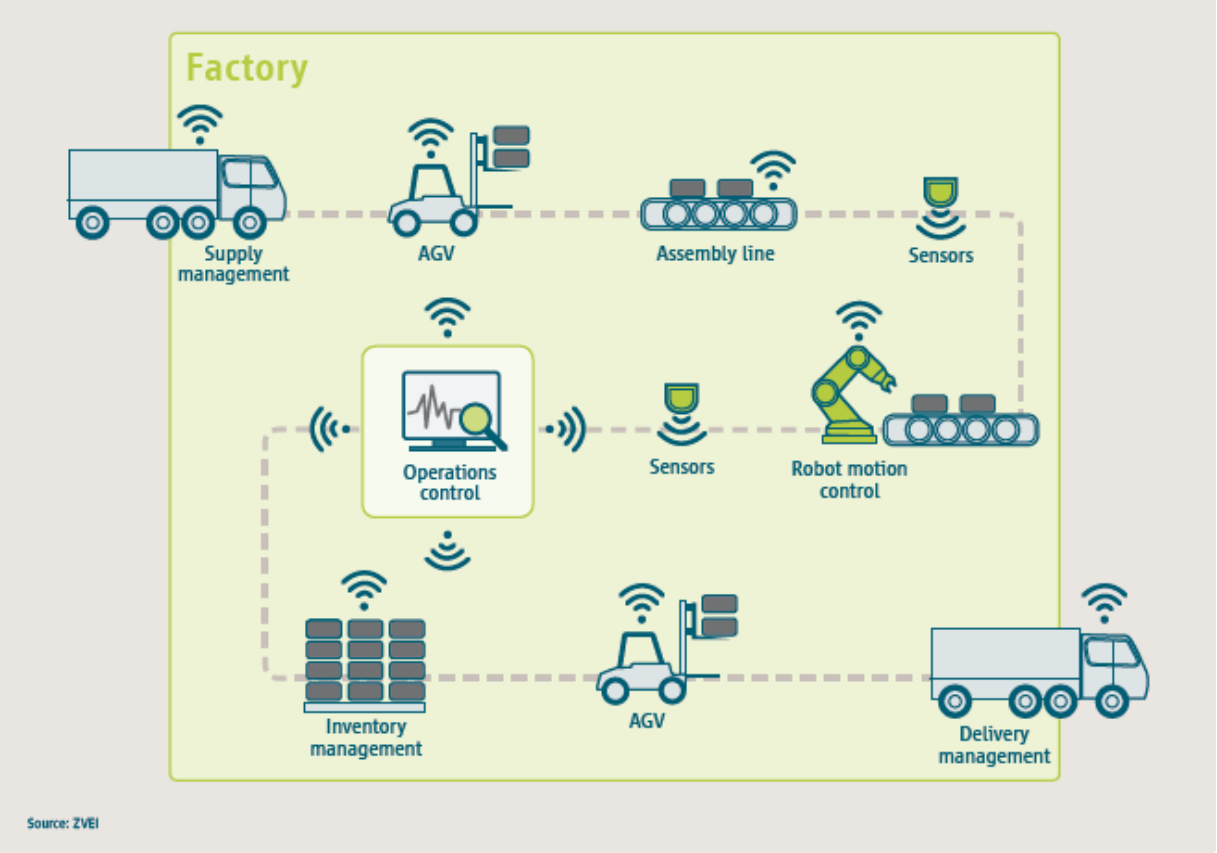
While the PS-LTE systems offer great benefits in terms of data connectivity for new data-oriented applications, the progress of PS-LTE adoption will be gradual. The complexities of integrating PS-LTE with legacy systems will be time-consuming. Moreover, the government funding and bureaucracy at both local and federal levels will take time for PS-LTE projects to get "green-lighted." Long decision-making processes at government agencies and lumpy funding cycles will slow the pace of PS-LTE adoption. The PS-LTE ecosystem of network equipment and devices is growing, but it will be a long process for Private LTE to take hold in the Government sector overall.

Manufacturing (Smart Factory)

The industrial domain is very diverse with a large number of different use cases and requirements. In factory floors, manufacturers rely on diverse wired network technologies for factory automation. The industrial communications market has been shifting away from traditional Fieldbus technologies (PROFIBUS, Modbus-RTU, CC-Link, etc.) to Industrial Ethernet (EtherNet/IP, PROFINET, EtherCAT, etc.).[4] According to its recent annual study of the industrial communications market, Industrial Ethernet has surpassed traditional Fieldbus making up 52% of the global market (rising from 46% in 2017) with EtherNet/IP holding the largest share at 15% of the market. Meanwhile, traditional Fieldbus has been declining – 42% share (declining from 48% in 2017). Meanwhile, Wireless (Wi-Fi and Bluetooth) has been growing fast and held 6% market share as "cable-free" connectivity offers flexibility for system integrators.[5] The fragmented industrial communications market share reflects the diversity of the market and proprietary industrial Ethernet protocols that numerous automation suppliers support. In the past couple of years, there is a trend towards Time Sensitive Networking (TSN) to enable interoperability among numerous proprietary industrial Ethernet protocols via standard Ethernet to address deterministic transfer in industrial IoT use cases.

As manufacturers hear about 5G URLLC features that offer deterministic response times to support low-latency applications, manufacturers are excited by the possibility of 5G enabling a wide range of different use cases and the possibility of converging the fragmented industrial communications technologies in the wired space as mentioned above. Moreover, manufacturers are excited about the possibility of 5G becoming the standard wireless technology that offers deterministic wireless transfer of data.

[4] HMS Networks is an independent industrial communication solutions supplier based in Sweden. The company has been releasing annual study of the industrial communications market.
[5] HMS Industrial Network market share study, Feb 2018



Source: 5G-ACIA

Figure 6. Illustration of application areas of 5G in manufacturing

As illustrated above, manufacturers see 5G application in manufacturing ranging from supply logistics to robotics to operations control, inventory management, and delivery management. A key desire, as articulated by the industry body, 5G Alliance for Connected Industries and Automation (5G-ACIA), is for 5G to support the various industrial Ethernet and TSN features so that it can easily integrate into the existing wired automation processes and infrastructure.

The manufacturing market is maturing in its approach to 5G. In particular, 5G-ACIA's "5G for Connected Industries and Automation" white paper articulates some of the high-level automation procedures and required network requirements in terms of availability, cycle time, and data payload and device density – ranging from most challenging (motion control) to less demanding (process automation) use cases in terms of latency and reliability. Based on this collaborative work, use cases are becoming defined so that Private 5G network suppliers can provide tailored products to suit the specific cases. Overall, growth will be slow due to the long time cycles involved with construction of new factories… but we see the groundwork taking place to enable 5G to begin taking market share.

3 PRIVATE WIRELESS NETWORK TECHNOLOGY OPTIONS

Private wireless network technology options are many. From low speed (WirelessHART) to high speed (Wi-Fi, LTE, etc.), licensed (LTE, 5G) to unlicensed (MulteFire) spectrum, and short range (ISA 100.11a) to long range (WiMax), one can find multitude of options available depending on region, spectrum availability, and industry segments. We have highlighted a few "mainstream" private wireless technologies in use today.

WirelessHART (IEC 62591)

WirelessHART is an international wireless sensor networking technology developed for field device networks. The protocol operates in the 2.4 GHz unlicensed band (typically from 2.40 – 2.48 GHz) using the IEEE 802.15.4 standard, which is the basis for many other low-power, low data rate, wireless personal area network technologies including ZigBee, 6LoWPAN, and ISA 100. In 2010, the technology was approved by the International Electrotechnical Commission (IEC) and sometimes is referred by its standard designation, IEC 62591.

As its name implies, WirelessHART adds wireless capabilities to the Highway Addressable Remote Transducer (HART) protocol. In addition, it maintains compatibility with 40 million field instruments that support HART technology according to FieldComm Group.[6] The technology targets sensors and actuators used in environmental health and safety applications such as safety showers in chemical plants, condition monitoring of oil and gas pipelines, and flexible manufacturing, to name a few.

[6] FieldComm Group (www.fieldcommgroup.org) is a global standards-based member organization consisting of leading process automation manufacturers, end users, and research organizations. The group was established in 2015 by combining the Fieldbus Foundation and HART Communication Foundation. The group develops and manages communication technologies including Foundation Fieldbus, HART, and Field Device Integration (FDI) technologies for the process industries.

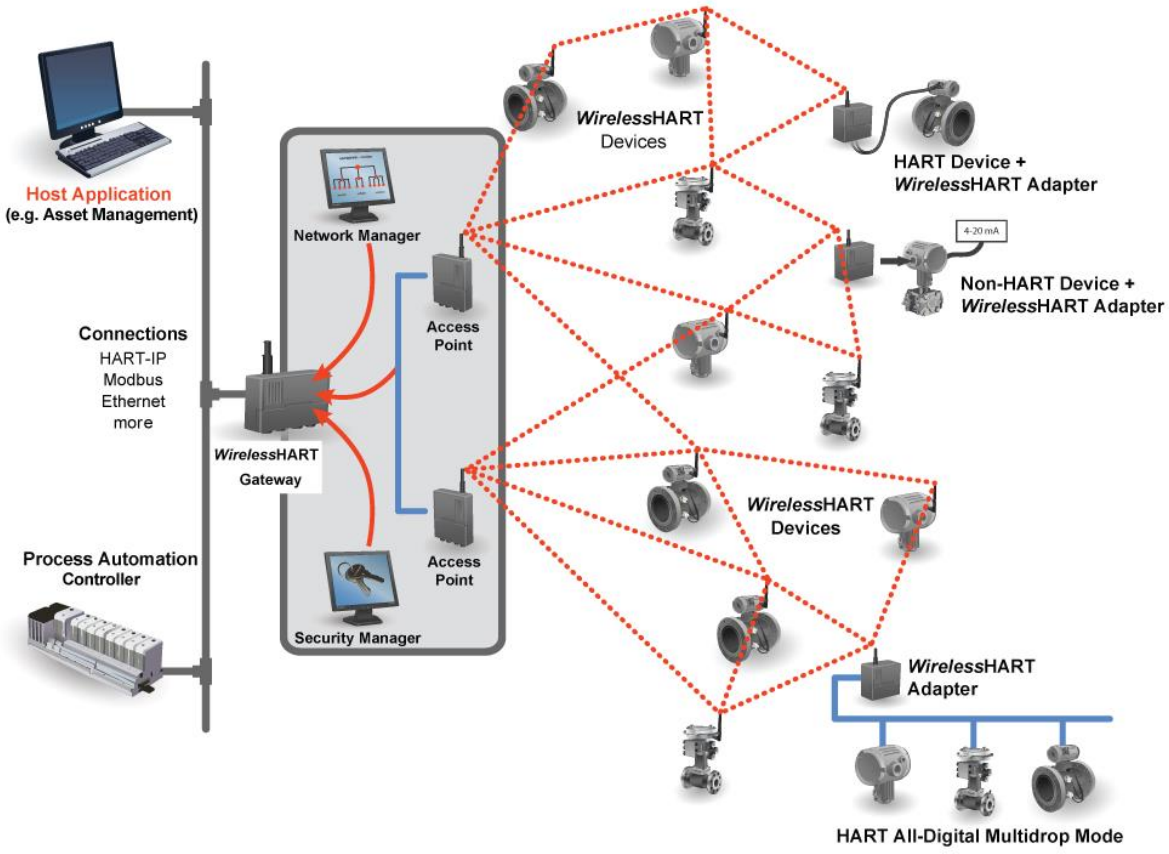
Source: Automation.com

Figure 7. A gateway (left) communicates with multiple WirelessHART field devices (right)

WirelessHART uses mesh networking to extend the range of the network and provide multiple paths to increase reliability in difficult radio environments. As illustrated below, a WirelessHART network is comprised of three main elements:

1. Wireless Field Devices - connected to process or plant equipment;
2. Gateway – facilitate communication between field devices and host applications connected to backbone plant communications network; and,
3. Network Manager – configures the network and handles overall communication messaging between devices and network management.

It should be noted that field devices can have WirelessHART built in or an adapter can attach to a HART-enabled device. Depending on specific application, the WirelessHART supports different messaging modes including broadcasting process and control values, ad-hoc request and response, and block transfers of large data.



Source: FieldComm Group

Figure 8. WirelessHART Mesh Network

The Network Manager, which can be integrated into a Gateway, controls RF resources at the physical layer, namely 15 RF channels in the 2.4 GHz band. The protocol uses time synched TDMA/CSMA wireless meshing for redundant paths and 128-bit AES encryption for security.

ISA 100.11a

ISA 100.11a is a competitive alternative to WirelessHART. It was developed through the International Society of Automation (ISA), a US-based organization made up of automation professionals. Although ISA 100.11a is in many ways similar to WirelessHART – both using IEEE 802.15.4 and designed for the same purpose, there are some key differences reflecting the design goals of the two competing standards. One, ISA 100.11a uses IPv6 addressing; thus there is no practical address limitation. In comparison, a single WirelessHART network is limited to 30,000 addresses. In WirelessHART, multiple access points in parallel can merge subnets into a large address space. Secondly, ISA 100.11a supports three different channel hopping algorithms, and users must purchase devices that support channel hopping algorithm that is compatible with others. By contrast, WirelessHART dictates the channel hopping algorithm by design, so interoperability across different manufacturers are guaranteed. Another major difference is that WirelessHART devices must support routing

by design, but for ISA 100.11a, this is optional. Furthermore, while WirelessHART by design supports well-known HART commands and features found in many legacy control systems, ISA 100.11a application layer allows devices to support other protocols through tunneling.

In summary, ISA 100.11a is designed for flexibility and scalability that potentially allows other Fieldbus network to be operated over the ISA 100.11a wireless mesh network. However, this flexibility and scalability can be a hindrance in a multi-vendor environment. By contrast, WirelessHART is designed for ease of deployment and interoperability. Practically, ISA 100.11a is more suited to a single-vendor implementation since much of the flexibility and scalability requires careful network design and configuration.

Wi-Fi (IEEE 802.11)

Private wireless networking arose from the needs of various enterprises to create their own networks to support wireless use cases. The IEEE 802.11 standards along with the Wi-Fi ecosystem has provided a long technology roadmap for the industrial wireless segment for many years. To meet high requirements in terms of volume of data communication traffic and devices, Wi-Fi roadmap continues to advance from 802.11b, 802.11n, 802.11ac, and now to 802.11ax.

The latest 802.11ax, or "Wi-Fi 6" as it is marketed, is especially pertinent to industrial applications as it promises greater efficiency for high-density connections. In other words, it promises higher capacity and more connections in dense environments. Initial claims show 4x increase in capacity compared to 802.11ac and improved coverage. The higher efficiency is achieved from a few key features found in 802.11ax:

- 8x8 MU-MIMO on both the 2.4 and 5 GHz bands – increase capacity
- OFDMA – improves network efficiency and reduces latency
- Scheduled access
- WPA3 security

Comparison of technical feature sets between 802.11ac and 802.11ax is shown below.

	802.11ac	802.11ax
Frequency bands	5GHz	2.4GHz and 5GHz
Channel sizes	20, 40, 80, 160 MHz	20, 40, 80, 160 MHz
FFT sizes	64, 128, 256, 512	256, 512, 1024, 2048 (four times larger)
Subcarrier spacing	312.5KHz	78.125 kHz (four times narrower)

OFDM symbol duration	3.2 usec + 0.8/0.4 usec cyclic prefix	12.8 usec + 0.8/1.6/3.2 usec cyclic prefix (four times longer)
Modulation (highest)	256 QAM	1024 QAM
Data rates (peak)	433 Mbps (80MHz channel bandwidth, 1 spatial stream)	600 Mbps (80MHz channel bandwidth, 1 spatial stream)
	6.9 Gbps (160MHz channel bandwidth, 8 spatial streams)	9.6 Gbps (160MHz channel bandwidth, 8 spatial streams)

Source: Mobile Experts, National Instruments

Figure 9. Key technical features of 802.11ax vs. 802.11ac

As noted above, 802.11ax operates in both 2.4 and 5GHz bands. More importantly, it significantly increases the number of subcarriers while preserving the existing channel bandwidth. Larger OFDM FFT sizes, narrower subcarrier spacing, and longer symbol time, in aggregate, improves robustness and efficiency while keeping the data rates the same as 802.11ac. In fact, with higher modulation support for 1024 QAM, the 802.11ax provides a higher maximum data rate. More importantly, though, it provides higher efficiency in multipath fading environments. With the higher number of subcarriers, the 802.11ax can more efficiently support simultaneous client devices by effectively divvying up the frequency.

Like 802.11ac, 802.11ax devices use explicit beamforming to direct data packets simultaneously to multiple users who are spatially separated. While the 802.11ac only defined MU-MIMO on the downlink, the 802.11ax standard defines uplink multiuser mode as well in which simultaneous data transmission from multiple client devices to an access point is possible. Another key addition of the 802.11ax standard is that it has defined two different ways of multiplexing users: Multiuser MIMO (MU-MIMO) and Multiuser Orthogonal Frequency Division Multiple Access (MU-OFDMA). In essence, 802.11ax borrows the underlying OFDMA technology used in LTE base stations to centrally manage multiple client devices, thus enabling more efficient access to a radio channel.

Also, the resource scheduling in the uplink increases efficiency by moving away from contention-based resource allocation found in 802.11ac to scheduling approach like LTE. With a combination of downlink and uplink MU-MIMO and MU-OFDMA, the 802.11ax is expected to support four times the average user throughput of 802.11ac. With combinations of these techniques and higher physical data rates, 802.11ax is expected to improve user throughput and extend coverage with higher 8x8 MIMO, especially in dense environments, which has been an Achilles' Heel for Wi-Fi relative to LTE. Note that the MU-OFDMA and resource scheduling will improve contention between clients that share an access point, but not for users on different access points.

Wi-Fi products used in industrial automation projects are typically called "Industrial WLAN" systems with hardened casings to withstand harsh environments and typically deployed in the context of a wider scalable LAN deployment with special considerations for security and redundancy for reliable communication as well as intelligent analytics to derive pertinent information for industrial automation.

Despite all of the improvements listed above, one drawback of Wi-Fi results from its success. For example, seaports using Wi-Fi based automation have been shut down because of rogue Wi-Fi hotspots on board the cargo ships. The improvements of 802.11ax such as scheduling will not be able to solve some of these fundamental challenges.

WiMax (IEEE 802.16e)

If Wi-Fi is considered a "mid-range" private wireless technology, WiMax is its long-range "cousin." WiMAX solutions are typically used in wide-area private wireless networks to extend IP networks over long distances to fixed and mobile devices such as in Oil & Gas and Utility industry applications that cover very large areas. Some of the key features added to the IEEE 802.16e standard which was approved in 2005 include the following:

- Mobility support (soft and hard handoff between base stations) added to make the IEEE 802.16e standard "mobile WiMax"
- Scalable OFDMA for better spectral efficiency
- Antenna diversity and HARQ
- Adaptive antenna and MIMO
- Better channel coding through LDPC
- Downlink sub-channelization for the capacity-coverage tradeoff
- Added QoS for VoIP application

While LTE has taken over the general mobile broadband "race," WiMax has found a niche in industrial applications leveraging the technology in 2.5 and 3.5 GHz lightly licensed spectrum bands. One concern currently for enterprises stems from the longevity of WiMax equipment and suppliers. Enterprises are legitimately concerned that support for their WiMax equipment will not exist in the future.

LTE Licensed

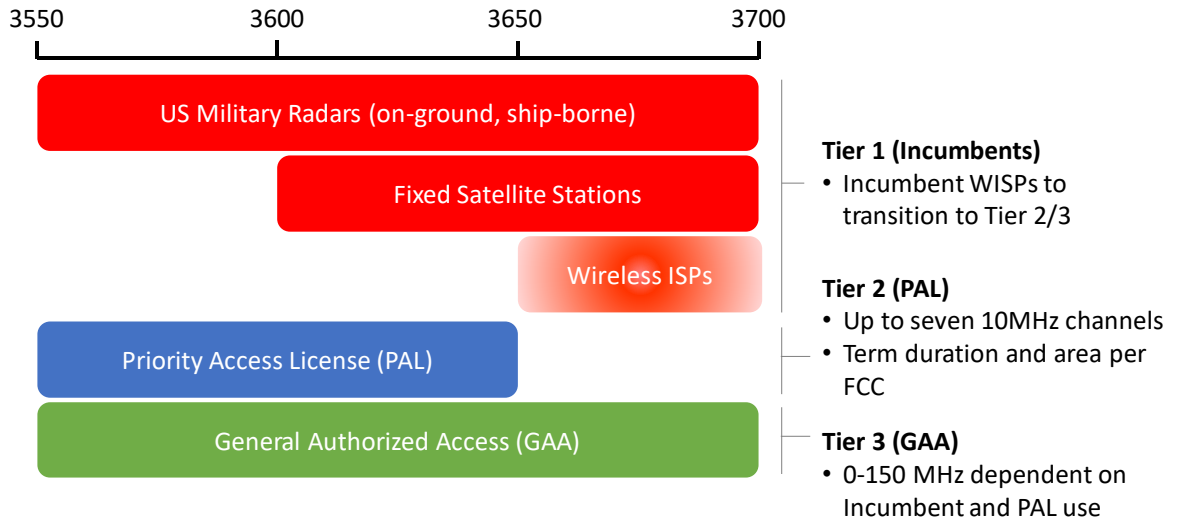
LTE offers a broad ecosystem of equipment and device suppliers. For some industry players looking to fully own private wireless network – from spectrum all the way to the entire communications infrastructure, LTE offers a wide-area, high-bandwidth IP networking option. For some utilities with licensed spectrum, deploying LTE network provides robust network capabilities as well as long technology roadmap that is supported by a multitude of suppliers. For example, SouthernLinc, a wireless ISP subsidiary of Southern Company, has

deployed its own LTE network in its southeastern footprint to not only support its Utility telecommunications network but also to offer mobile broadband services to consumers.

For many utilities who have deployed 900 MHz MAS radios back in the 1990s, it is becoming clear that they need a long-term technology that offers robust supplier ecosystem that will be around for another 20-30 years based on their current predicament where it is difficult to find suppliers to maintain an aging MAS infrastructure.

OnGo/CBRS (LTE on Shared Spectrum)

The Federal Communications Commission (FCC) in its 2015 ruling established Citizen Broadband Radio Service (CBRS) for shared commercial use of the 3.5 GHz (3550-3700 MHz) band with incumbent military radars and fixed satellite stations. Under the plan, the use of the shared spectrum is prioritized, in descending order, by the three class of users: Incumbent users first, then Priority Access License (PAL) users, and finally General Authorized Access (GAA) users (see Figure below). The priority of spectrum access is governed by Spectrum Access System (SAS) which maintains a database of all OnGo-certified base stations and works with environmental sensors known as Environmental Sensing Capability (ESC) to mitigate possible interference to the Incumbent users.



Source: Mobile Experts

Figure 10. CBRS three-tier shared spectrum licensing structure

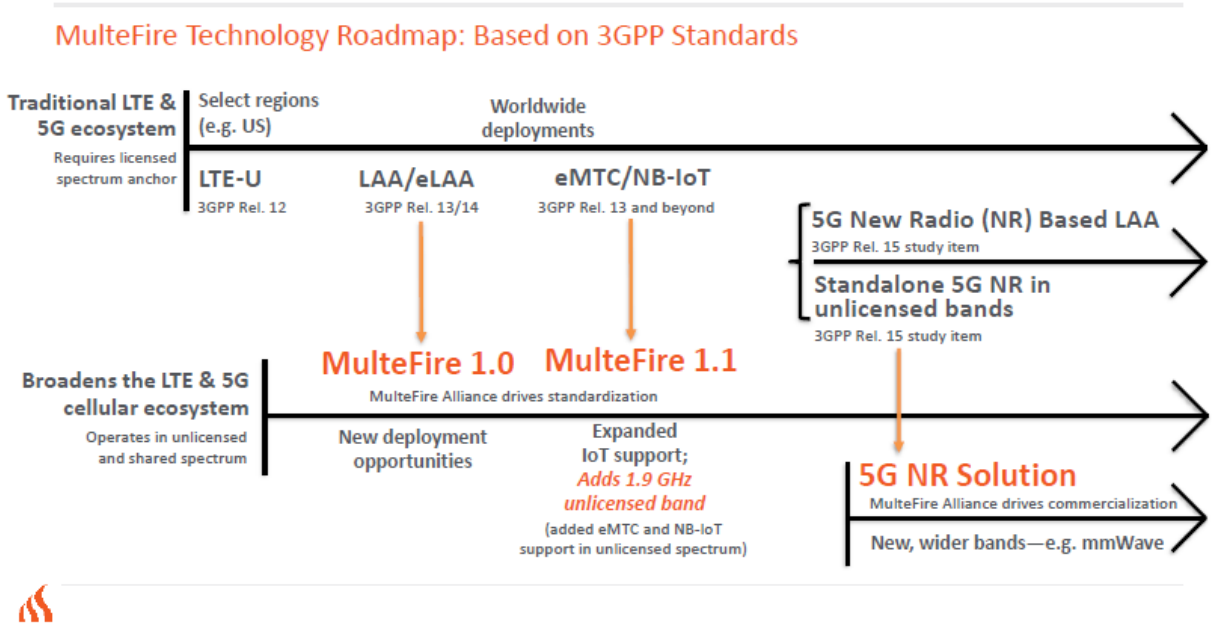
The industry consortium, CBRS Alliance, has been working closely with government agencies and other industry bodies including FCC, NTIA, Department of Defense, ITS, and Wireless Innovation Forum to foster the development and commercialization of LTE operation in the CBRS band. The CBRS Alliance has drafted technical standards, established OnGo certification program, and named authorized test labs around the world to get ready for commercial deployments. In July 2018, the FCC released its Public Notice of Initial

Commercial Deployments which is a major milestone for the stakeholders, taking OnGo commercial deployment one step closer to reality. The on-going SAS compliance through real-world testing plus FCC approval of submitted deployment sites is expected to transition onto commercial launch in 2019.

The CBRS/OnGo technology is applicable for the US market only since this particular shared spectrum regime is regulated by the FCC in the USA. However, this shared spectrum licensing is carefully reviewed by regulators in other countries and regions to see if it can be applied in other markets.

MulteFire (LTE on Unlicensed Spectrum)

MulteFire builds on 3GPP standards to enable standalone cellular operation in an unlicensed or shared spectrum. By removing the requirement for licensed spectrum (e.g., the need for licensed 'anchor' carrier in LAA), MulteFire allows enterprises to deploy and operate their own private network for mobile broadband or IoT applications. MulteFire 1.0 augmented the 3GPP Release 13 and 14 specifications for LAA (carrier aggregation on the downlink) and eLAA (carrier aggregation on both downlink and uplink) to operate in the global 5 GHz unlicensed spectrum.



Source: MulteFire Alliance

Figure 11. MulteFire is aligned with 3GPP standards to broaden LTE and 5G in unlicensed

MulteFire 1.1, which was recently released in December 2018, brings optimizations especially for IoT applications with support for NB-IoT and eMTC in unlicensed spectrum. Moreover, it has expanded spectrum support in 1.9 GHz focusing on Japan and lower bands 800/900 MHz.

Finally, it enhances MulteFire 1.0 services in the 5 GHz unlicensed band. Some of the key features of MulteFire 1.1 include:

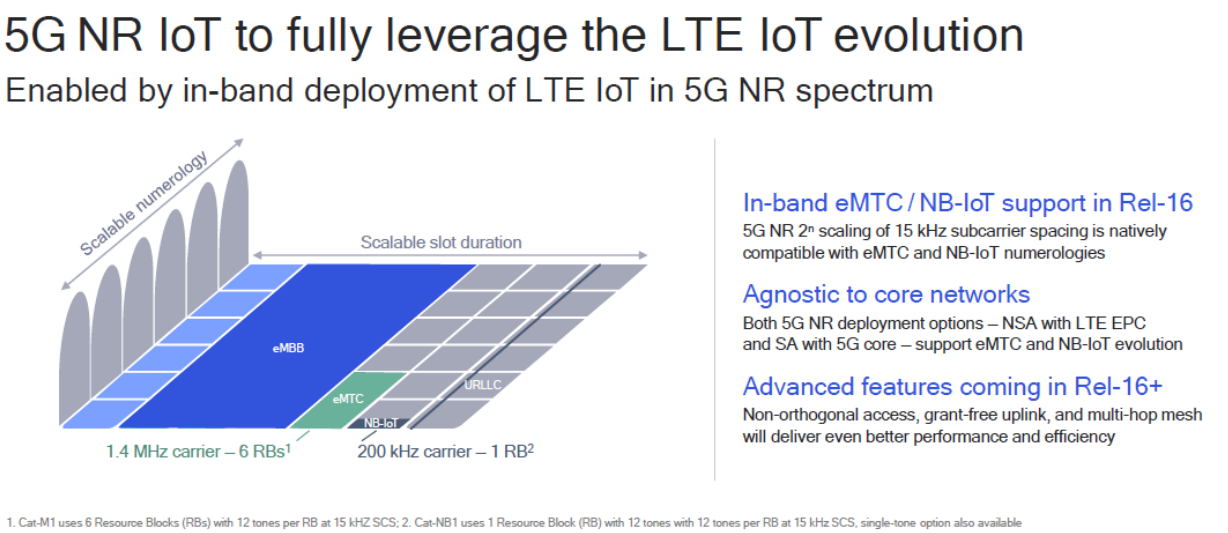
- 5 GHz broadband enhancements
  - Grant-less uplink for faster uplink transmissions
  - Wideband coverage enhancements to balance uplink and downlink coverage
  - Autonomous UE Mobility which performs autonomous handover without explicit network command resulting in more robust mobility
  - SON features for LTE
- IoT optimization features
  - eMTC-Unlicensed (1.4 MHz)
  - NB-IoT-Unlicensed (180 kHz)
  - IoT range expansion in 5 GHz (10/20 MHz carrier bandwidth),
- New spectrum bands focusing on IoT
  - 2.4 GHz unlicensed use for eMTC
  - 1.9 GHz targeting sXGP in Japan (unlicensed part in Band 39 and also known as DECT spectrum globally)
  - 800/900 MHz ISM spectrum for NB-IoT

The additional unlicensed spectrum support in MulteFire 1.1 targets enterprise IoT use cases leveraging readily available unlicensed spectrum while closely aligning with 3GPP standards to keep device cost considerations in mind. The eMTC-U in the 2.4 GHz band uses a single physical layer design that meets ETSI and FCC regulations to broaden the appeal to multiple markets while keeping development and ultimately device cost in check. Due to a 20 dBm output power limitation imposed by regulations, eMTC-U density and range will be limited as compared to licensed eMTC use cases but should be applicable in "short-distance" urban settings. Meanwhile, MulteFire NB-IoT-U is specifically targeting 902-928 MHz ISM band governed by FCC and 863-870 MHz band governed by EU regulations. For regulation compliance, lower physical layers in MulteFire NB-IoT-U is different from cellular NB-IoT for regulatory compliance while keeping the higher layer protocols remain the same. (For details, please refer to the MulteFire 1.1 Specification.[7])

5G URLCC

Ultra Reliable Low Latency Communication (URLCC) is one of the important design goals of 5G NR. 5G URLCC targets an end-to-end latency of less than 1ms which is an order of improvement over LTE. To reduce the latency, 5G NR introduces a flexible and dynamic frame structure that can handle broadband data and highly reliable, low-latency bursts. More specifically, the symbol length can change along with the slot length.

[7] MulteFire 1.1 Specification and technical white paper can be found at www.MulteFire.org

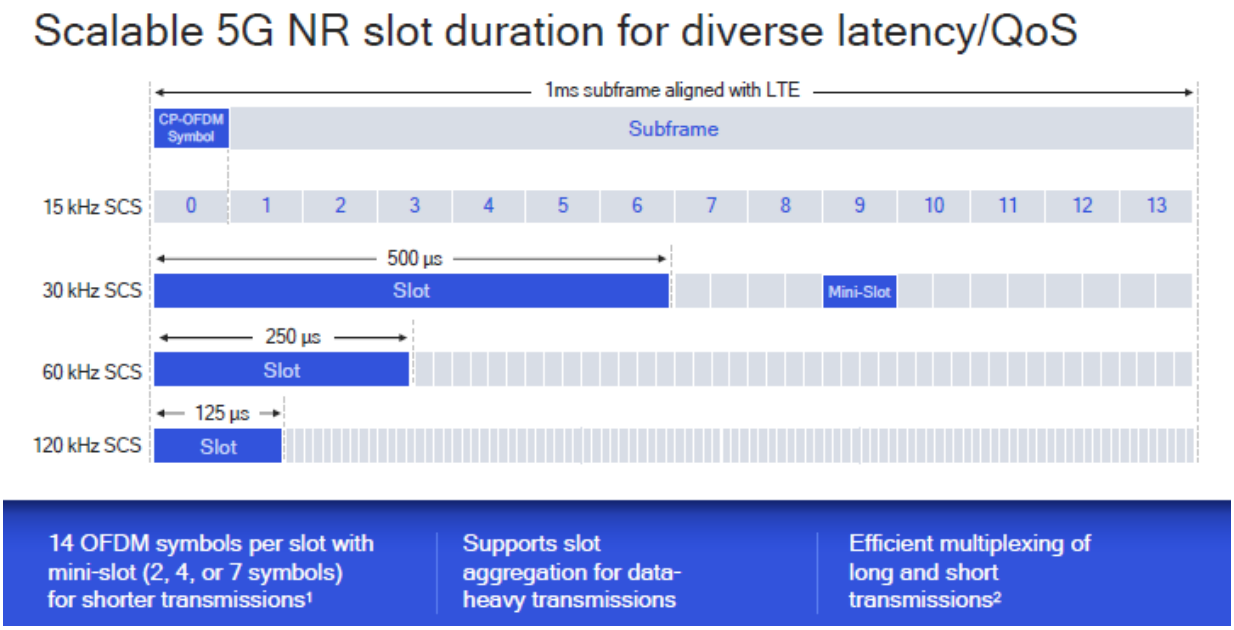


Source: Qualcomm

Figure 12. 5G NR flexible framework supports low-latency applications

The 5G NR has multiple improvements over LTE in terms of latency, including:

- The Transmission Time Interval (TTI) can be set to a much shorter time. Where LTE has a fixed TTI of 1 ms, in 5G the 'mini-slots' can be set to allow TTI in the range of 140 microseconds.
- The shorter slot lengths go along with higher 'numerology,' which refers to the sub-channel spacing and basic setup of the OFDM access. The sub-channel spacing is typically locked into the hardware design, so changing the standard to allow for narrower sub-carrier spacings means that IoT can be quick while operating in a narrow band.
- The processing in 5G NR is quick, using only 1-2 symbols in the UE, and 7-14 symbols in the gNodeB. In this way, a message can be answered quickly.
- Grant-free uplink messages are possible with 5G NR, simplifying the control signals necessary to set up a link.
- Rapid Hybrid Automatic Repeat Requests (HARQ) are possible, greatly improving latency under marginal radio conditions.
- Puncturing is available with 5G NR in Release 16, so that other data traffic can be interrupted with mission-critical traffic without loss of continuity.



Source: Qualcomm

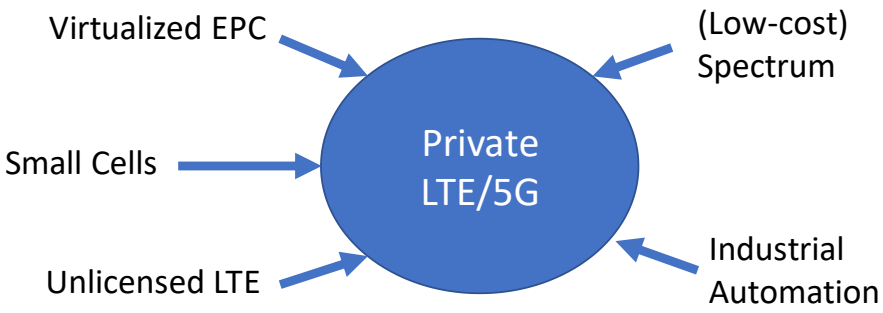
Figure 13. Scalable 5G NR slots are much shorter than 1ms LTE subframe

Proprietary Wireless

In addition to standards-based technologies driven by IEEE or 3GPP, there are many proprietary wireless technologies in use today across different industries and spectrum bands. Using combinations of frequency hopping spread spectrum, error-correction coding, network topology (meshing), and other physical and MAC layer techniques, multiple vendors have found niche market across different industries and geographies. For example, Freewave's radio solutions have been applied in Oil & Gas and military applications for many years. Meanwhile, Rajant's narrowband RF meshing solution has been used in many surface mine applications. Industries have different private wireless network requirements spanning coverage range, data rates, IoT connection density, reliability, etc. Moreover, spectrum availability (and cost) will drive the technology solution choice. The landscape for private wireless technology choice will remain vast and diverse for many years to come.

4 LTE AND 5G AS WIRELESS ENTERPRISE NETWORK

Mobile network trends in Small Cells, virtualized Core, and spectrum availability are creating an opportunity for Private LTE use in enterprises as a "bite-size" technology solution offerings that can be more enticing for more and more enterprises who were priced out of adopting LTE technology for stringent networking requirements in certain industries. Where these networks required a huge investment in the past, virtualization is allowing the network to be scaled down to an affordable size.



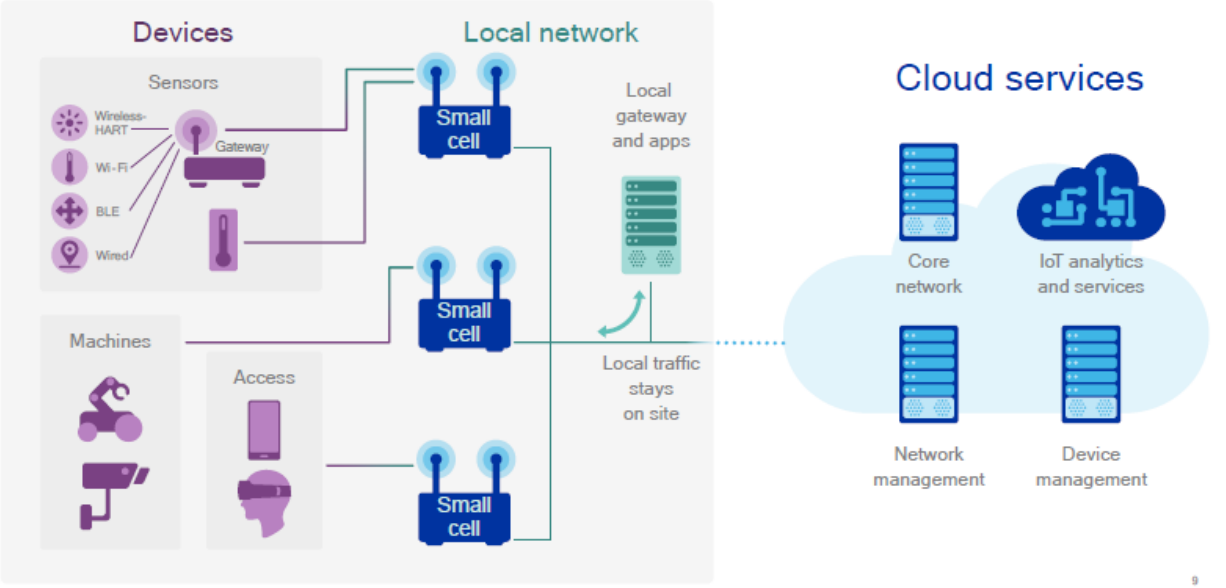
Source: Mobile Experts

Figure 14. Trends driving Private LTE in Enterprise

Private LTE Architecture

Private LTE architecture consists of Virtualized EPC Core, Indoor and Outdoor Radio Units (i.e., Small Cells and in some cases, high-power Macrocell-class radios), and end-user devices (i.e., CPEs and cellular IoT sensors for automation). Depending on use case and deployment scenario, a virtualized EPC core can reside locally at a venue or site or can be located in a remote location (perhaps at a headquarters) to manage core functions like service provisioning, device authentication, etc. Core EPC and other software functions like SON can be run on COTS server and can be scaled up or down depending on the scale of network deployment and the number of end devices under management. We have seen vendors offer different "sizes" of EPC core servers or offer "as a service" in the cloud.

Depending on the particular Private LTE deployment scenario, different Indoor or Outdoor Radio Units (i.e., small cells) can be deployed in order to provide the right mix of coverage and capacity. In a large surface mine, it is feasible to have one high-power Outdoor Radio Unit (macrocell) provide a "blanket" coverage in an open-pit mine while multiple mid-power Outdoor Radio Units (outdoor small cells) providing strategic coverage and capacity for broadband and IoT services. In a smart factory scenario for Manufacturing, a high number of Indoor Radio Units (indoor small cells) could provide coverage indoors to service thousands of cellular IoT sensors for various automation tasks.



Source: Qualcomm

Figure 15. Private LTE Architecture

Benefits and Challenges of Private LTE

Enterprises in different industries must weigh the benefits and challenges of deploying Private LTE in the context of objectives and fully considering short-term costs of making a transition in a brownfield environment and long-term benefits.

Benefits of Private LTE (and 5G) include the following:

1. *Reliability and Predictability* – With scheduling MAC, LTE offers predictable and reliable wireless links.
2. *Higher QoS* – LTE offers a flexible quality of service (QoS) framework with granular traffic classification and prioritization.
3. *Security* – Cellular security framework is end-to-end meaning that all transmitted data between the device and the network is encrypted.
4. *Interoperability* - As a part of 3GPP standards and certification, LTE network equipment and devices from suppliers are interoperable.
5. *Long Range/Coverage* - LTE generally offers long range connectivity (depending on the spectrum). Industrial automation especially in wide-area contexts, such as in Mining and Oil & Gas, favors LTE and 5G.
6. *Mobility* – LTE provides mobility scenarios better than Wi-Fi or other point-to-multipoint wireless systems. Mobility is a foundational pillar of cellular.

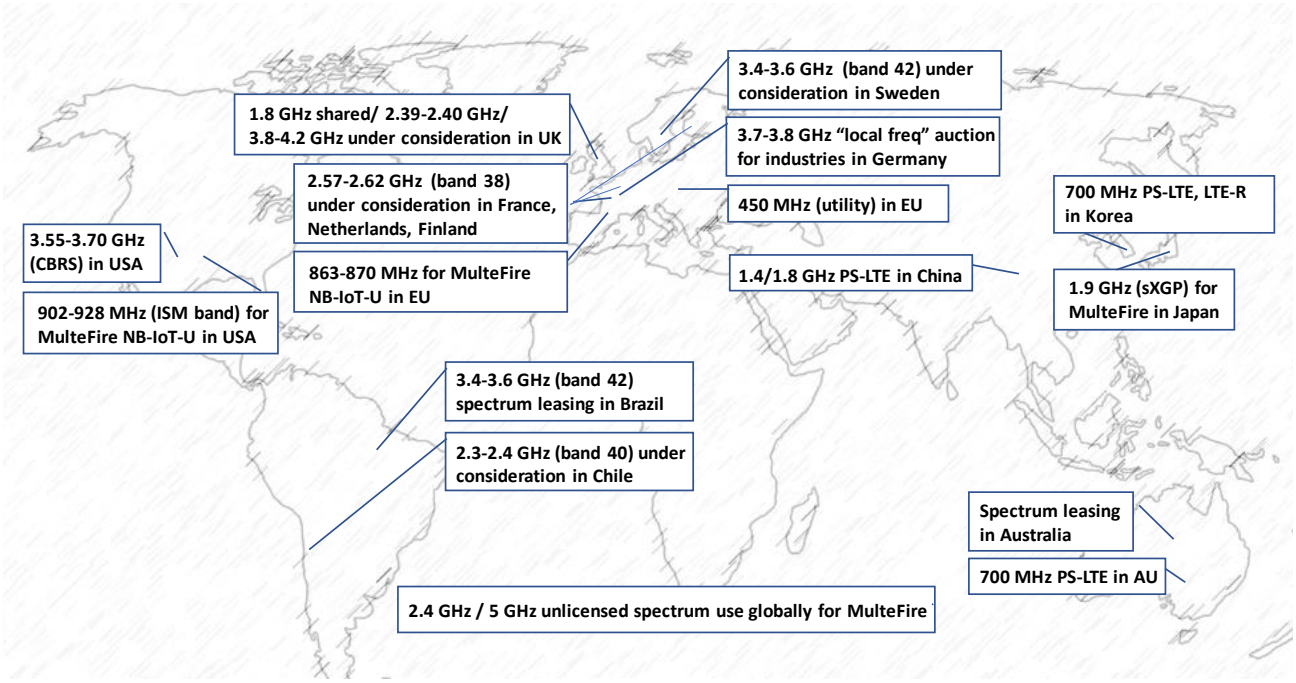
7. *Global Standard and Ecosystem* - (3GPP) LTE offers a long-term technology roadmap to 5G and beyond and a robust ecosystem of suppliers.

Meanwhile, here are some of the challenges of Private LTE:

1. *Spectrum* – While spectrum choices are increasing across licensed, shared, and unlicensed bands, wide and dedicated spectrum for localized services is preferred. Many times, the licensed spectrum available is too narrow for adequate LTE/5G service, with 500 kHz or 1 MHz chunks of spectrum in the 900 MHz range as examples. Depending on the industry and specific use cases, Private LTE in shared (CBRS) or unlicensed (MulteFire) spectrum may not be desired. For example, a high automation application requiring real-time response times, dedicated spectrum may be the only way to go. While CBRS in the USA and the recently announced shared spectrum framework in the UK offer a glimpse of low-cost spectrum alternatives, commercial case studies are needed to assure some enterprises of the viability of Private LTE.
2. *Business Model* – For Private LTE operation in licensed spectrum, access to licensed spectrum is not straightforward. While leasing licensed spectrum from a mobile operator may be an option, proven business models are not clear for enterprises who are new to LTE. In particular, the operators struggle with the details of how to carve out excess spectrum in a limited area, and how to prevent interference with their public networks. There needs to be a more straightforward method of accessing spectrum for localized services for industry players.
3. *Channel Partners* – Industrial automation players like Siemens, ABB, Emerson, GE, and others are key go-to-market channel partners to many large industries. They provide end-to-end solutions including equipment and services. It is important for Private LTE equipment vendors to establish strategic partnerships with these players.

5 SPECTRUM OPTIONS FOR PRIVATE LTE

In addition to existing licensed spectrum available for Private LTE deployment through spectrum leasing, regulators seem more open to bringing more spectrum available for industrial use under a variety of licensing regimes, including traditional license auctions (for industrial players), shared spectrum use and unlicensed use. As illustrated below, spectrum options for Private LTE span from low 700/800 MHz bands for public safety and railway applications to mid-band (1.8 – 3.8 GHz) for industrial applications for "local" coverage. Also, MulteFire offers potential use of unlicensed spectrum in the 2.4 and 5 GHz bands for standalone LTE operations.



Source: Mobile Experts

Figure 16. Private LTE Spectrum Options Worldwide

450 MHz (Utility)

As Utilities look to transition from low data rate 900 MHz MAS radios to broadband systems, some European Utilities appear to be interested in LTE450 or Band 31 (452.5-427.5 MHz UL / 462.5-467.5 MHz DL). With a pair of 5MHz channels for downlink and uplink, it is not clear that this particular spectrum band would be sufficient to provide broadband IP services that many utilities desire. Despite favorable RF characteristics of long-range and network deployment economics, there may not be enough capacity for the long-term vision of many utilities. Despite these challenges, some European Utilities appear to be interested in this spectrum. According to 450 Alliance, an industry association of 450MHz spectrum

stakeholders, PGE has announced that it will build a nationwide LTE450 network for the Polish utility industry.[8]

700 MHz (Public Safety and Railway)

Many countries are gradually modernizing legacy public safety systems, such as TETRA, Tetrapol, and P25, to broadband LTE. Since public safety networks are focused on geographical coverage (vs. population coverage) first and foremost, most countries are adopting sub-1 GHz spectrum for the public safety system. Korean regulators chose LTE band 28 (718-728 MHz uplink / 773-783 MHz downlink) for dedicated Public Safety LTE (PS-LTE) that it is currently under construction. The Korean PS-LTE system will be extended to LTE-R railway and LTE-M maritime applications covering the country's entire rail network and coverage extension out to 100km offshore.

In the USA, the government has authorized the First Responder Network Authority (FirstNet) to build and operate a nationwide PS-LTE system and allocated LTE band 14 (758-768 MHz downlink / 788-798 MHz uplink) for the PS-LTE spectrum. (It should be noted that Mobile Experts does not count FirstNet network investment in our Private LTE forecast since the FirstNet's hybrid model in which the dedicated PS-LTE RAN capacity can be shared with AT&T consumer broadband when not in use by the public safety users.)

Some countries are deploying a variety of spectrum bands for PS-LTE. In China, 1.4 GHz and 1.8 GHz has been used for building out PS-LTE networks in major cities. Huawei has reported using its "enterprise LTE" (eLTE) systems in many PS-LTE projects in key cities and provinces. In the UK, similar to the FirstNet hybrid model in the USA, an operator (EE) has been tapped to build out the Emergency Services Network (ESN) leveraging various LTE bands at the operator's disposal including 800 MHz, 1.8 GHz, and 2.6 GHz. Unlike the FirstNet model, no dedicated PS-LTE spectrum was assigned by the UK government.

The 700 MHz spectrum will be a strong contender for PS-LTE as other countries start their public safety modernization programs. The leading PS-LTE projects based on 700 MHz in the USA and Korea will have enabled an ecosystem of PS-LTE systems and devices. In addition, some may look to migrate their legacy systems to PS-LTE on 400 MHz. According to GSA, many countries are trialing PS-LTE system on this lower band to lessen the network investment on the number of radio sites.[9]

800/900 MHz (for Unlicensed NB-IoT)

With MulteFire 1.1, there is the possibility of extending NB-IoT applications in the 800/900 MHz unlicensed spectrum bands in the USA and Europe. For enterprise customers looking to extend NB-IoT applications on its "own" license-exempt spectrum, they can do so on the 902-928 MHz ISM band in the USA and 863-870 MHz band in Europe. Since MulteFire 1.1 has just been released, it is too early to determine how the chipset and device supplier ecosystem will evolve in fostering this ecosystem. The global scale of "licensed" cellular NB-

[8] 450alliance.org news, September 2018.
[9] GSA, "Public Safety LTE networks," July 2018.

IoT ecosystem will probably benefit this license-exempt version as well. It remains to be seen how much "private" NB-IoT demand there is vs. operator-controlled cellular NB-IoT offerings.

1.9 GHz sXGP band

Another spectrum band where LTE applications can be extended is in the 1.9 GHz unlicensed band that has been used for legacy DECT and PHS systems. The shared eXtended Global Platform (sXGP) technology forum is working to incorporate TD-LTE into the 1.9 GHz band. MulteFire has effectively co-opted sXGP to extend the Band 39 device ecosystem onto this band. Similar to PHS and DECT systems, MulteFire in 1.9 GHz can provide coreless phone service within an enterprise's private network. In addition, IoT services can be supported that require high data rate requirements.

2.4 GHz Unlicensed

While we have not seen strong adoption of Private LTE in 2.4 GHz unlicensed spectrum, Private LTE in the 2.4 GHz unlicensed spectrum is possible via MulteFire. With robust Wi-Fi usage in this band, however, it is not clear that there is a strong demand from the device vendors yet -- and strong willingness for chipset suppliers to invest. Mobile Experts believes that Private LTE adoption in the 2.4 GHz band will take some time to materialize. Private LTE adoption in other bands will come first before this band gets utilized.

2.6 GHz (Band 38)

The TD-LTE band 38 (2570 – 2620 MHz) is one of two main blocks of the spectrum being considered by several regulators in Europe for vertical campus use. (The other being 3.4-4.2 GHz C-band.) The 50 MHz of spectrum may be just enough spectrum for broadband services and other enterprise applications. This particular band is not widely used today. In fact, some European countries have not auctioned off this band yet. As regulators consider higher spectrum bands for 5G, regulators are considering spectrum bands dedicated for vertical industries to foster new business opportunities for operators and enterprises alike.

3.5 GHz CBRS (Band 48)

USA is close to opening up the CBRS (3550 – 3700 MHz) band, also known as Band 48 in 3GPP parlance, for commercial deployment. While the PAL auction is not likely until the first half of 2020, the market participants are expecting commercial deployments under GAA basis (akin to unlicensed band use) this year. Based on early initial commercial deployment plans submitted to the FCC, we expect a variety of different use cases ranging from fixed wireless broadband access, private LTE indoor and outdoor applications. Based on actual PAL auction rules, the long-term CBRS adoption for Private LTE will become more clear. We currently believe the current PAL rules generally favor big operators and may push out smaller players during PAL auction and limit enterprise adoption.

3.4 – 4.2 GHz C-bands

Many European countries are considering various C-band (between 3.4 – 4.2 GHz) for "local" frequencies that can be utilized for private LTE/5G networks at plants and vertical campuses.

In Germany, industrial players are seeking to acquire spectrum in the upcoming 5G auction. Many industry associations representing leading firms in the automotive, chemical, mechanical, and electrical industry are actively petitioning the Germany regulator to make available the 100MHz of 5G spectrum in the 3.7 – 3.8 GHz band for private 5G networks. Several German car makers and industrial companies including Volkswagen, Siemens, and BASF have already announced their intention to acquire 5G licenses for industrial use.

In the UK, Ofcom has released an interesting proposal on shared spectrum access recently.[10] The proposal for comments details spectrum allocation for private cellular networks which could be used by enterprises for various services including voice, data, and industrial IoT applications. The proposal outlines two ways. One, Ofcom proposes three shared spectrum bands (below) which companies can apply for low-power and mid-power deployment licenses for localized services:

- 1.8 GHz shared spectrum
- 2.3 GHz shared spectrum used for defense
- 3.8-4.2 GHz currently used by satellite ground stations and point-to-point fixed wireless links

Ofcom proposes to manage this shared spectrum access process directly at low cost. The second proposal for the shared spectrum framework is even more dramatic. Ofcom proposes sharing *existing* licensed bands for local access at some locations for a three-year license at a one-time fee of £950 per license. Effectively, this is a "use it or lose it" rule for mobile operators who may be "sitting" on spectrum licenses. While it is hard to believe that the second rule of localized licensing of mobile operators' national license would survive the rulemaking process, the shared spectrum, especially in the 3.8-4.2 GHz, would be a boon to Private LTE efforts in the UK.

5 GHz Unlicensed

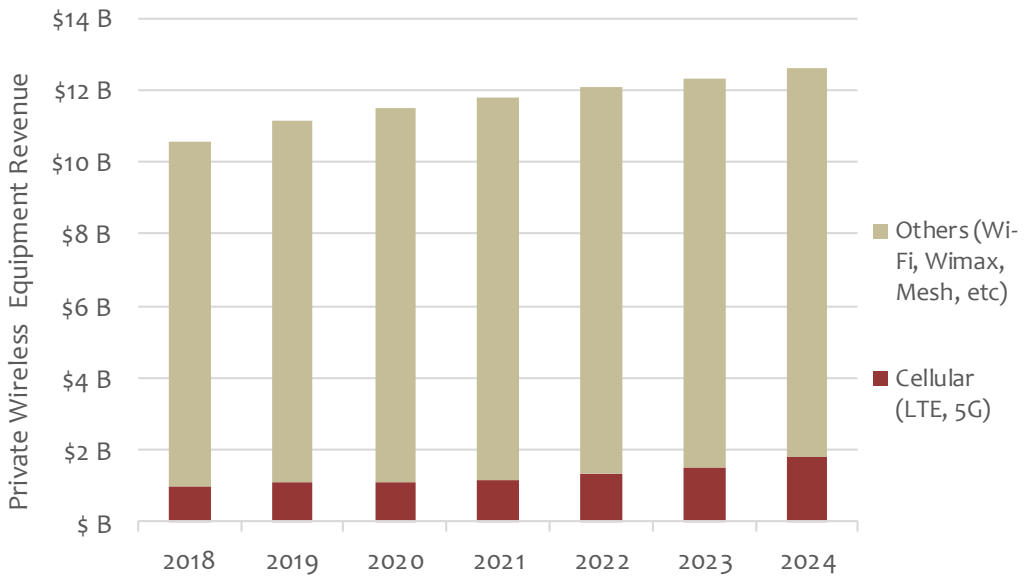
Similar to the MulteFire in 2.4 GHz, we have not seen strong adoption of Private LTE in 5 GHz unlicensed spectrum. With robust Wi-Fi usage in this band, it is not clear that there is a strong demand from the device vendors as of yet -- and strong willingness for chipset suppliers to invest. Mobile Experts believes that Private LTE adoption in the 5 GHz band will be limited with strong Wi-Fi usage in this band. Private LTE adoption in other bands will likely come first before this band gets utilized.

[10] Ofcom "Enabling opportunities for innovation," Dec 2018

6 PRIVATE CELLULAR (LTE/5G) OUTLOOK

Mobile Experts' definition of "Private LTE" refers to the enterprise-managed cellular network (which includes 5G) with dedicated equipment for local services. In contrast, "Public LTE" refers to the mobile operator-managed cellular network with shared infrastructure equipment for multiple services including consumer broadband and M2M services. For instance, a mining company's LTE network on using spectrum sub-leased from an operator would be considered "Private LTE" and the network equipment and CPE and IoT devices are counted in our forecast below. Meanwhile, the FirstNet Public Safety LTE network investment via AT&T is not considered "Private LTE" since that infrastructure investment is not solely dedicated to public safety traffic. That type of hybrid model in which private enterprise traffic is serviced through mobile operators' public network is not considered "Private LTE" system.

The Private LTE market looks bright--almost doubling in equipment revenue from below $1.0 billion in 2018 to about $1.8 billion in 2024. However, it will remain a small portion of the overall private wireless market in the context of many other technologies such as WiMAX, WirelessHART, Wi-Fi, RF meshing, etc. that have long served different industries from mining to manufacturing over a couple of decades. At the end of our forecast period in 2024, the private LTE/5G equipment market is expected to reach about 15% of the overall private wireless networking sector gradually increasing its share as industrial players realize the benefits of LTE and 5G in modernizing their operations from vast mining fields to highly dense manufacturing floors. Because of entrenched ecosystems of alternative technology solutions and long sales cycle in industrial segments, Mobile Experts forecasts a gradual penetration of Private LTE and 5G overall, but the pace of adoption will differ widely by industry verticals and spectrum availability.

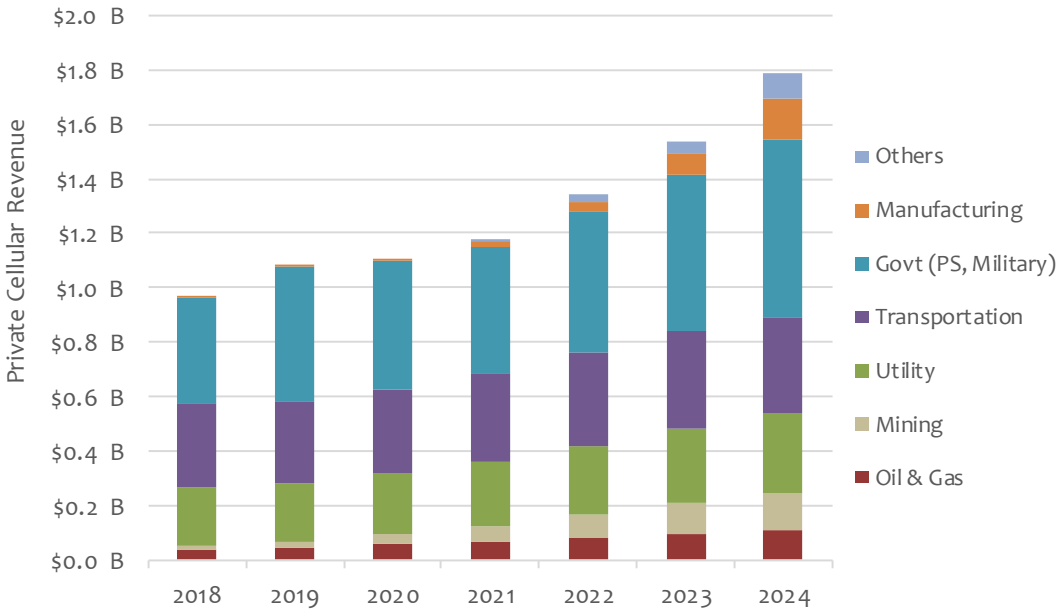


Source: Mobile Experts

Chart 2: Private Wireless Equipment Revenue, Cellular vs. Others

Private LTE Forecast by Industry

The Private LTE adoption varies widely by industry. For large industry verticals that generally require wide area coverage like railway (under Transportation), public safety (under Government), and smart grid (under Utility) applications, private cellular solutions using high-power macro towers provide economical ways to connect end devices and applications. For these reasons, the Government sector which includes Public Safety and military applications, the Transportation sector including railways, transportation hubs, and shipping ports represent the largest industry segments for the Private LTE market.



Source: Mobile Experts

Chart 3: Private Cellular Equipment Revenue, by Industry

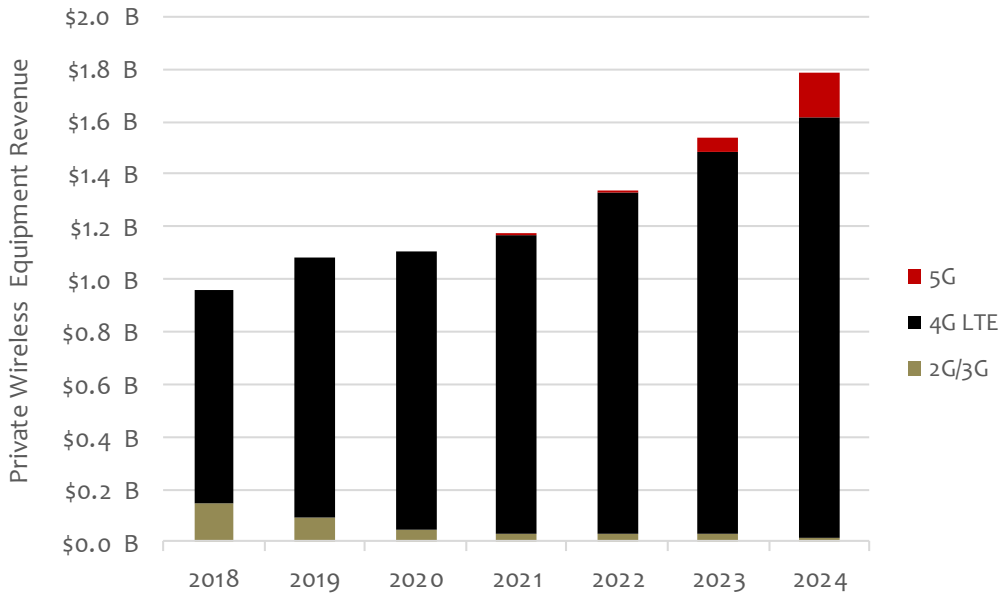
It should be noted that while our forecast shows a relatively smooth uptrend in Private LTE equipment market, actual sales should be lumpy, especially in the near term. Private LTE market is still in very early stages despite the sizable overall market today. Today's Private LTE market is mostly characterized by large railway projects in the Transportation sector, public safety rollouts and military applications in the Government sector, and selective smart grid networks being deployed by Utilities instead of using the "public" operator networks.

Starting from a very small base, the Manufacturing sector is expected to be the fastest growing sector (above 120% CAGR from 2018 to 2024) as very large manufacturers look to leverage low-latency and massive IoT capabilities of 5G to automate real-time functions on factory floors. Also, as the Mining sector continues to embrace full autonomy and safety and operational benefits that it brings, the Private LTE and 5G equipment market are expected to increase over 10x during the forecast period.

Private LTE Forecast by Technology Generations

The cellular technology shift in the industrial context mirrors the wider consumer broadband adoption trend. For the most part, cellular technology used in private wireless networking is dominated by the use of LTE. This isn't too surprising given that LTE can support general broadband communication and IoT applications. Except for very stringent latency and massive IoT requirements found in smart manufacturing settings, LTE is capable of supporting voice, data and video applications. The 5G uptake will be primarily driven by stringent network requirements associated with full autonomy in Mining and massive IoT and very low-latency in Manufacturing in our view. As the private LTE adoption in those

particular industrial segments ramps up in 2023, and beyond, we expect the 5G share to quickly ramp up as the overall 5G ecosystem expands and other industries also adopt the new capabilities of "Private 5G."

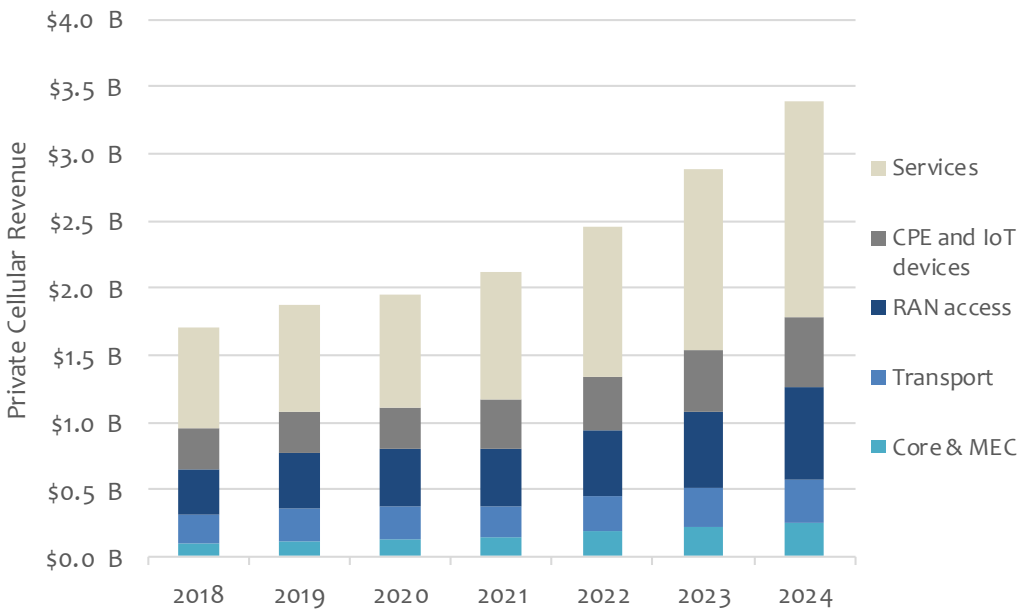


Source: Mobile Experts

Chart 4: Private Cellular Equipment Revenue Share by Technology Generation

Private LTE Revenue Forecast by Equipment and Services

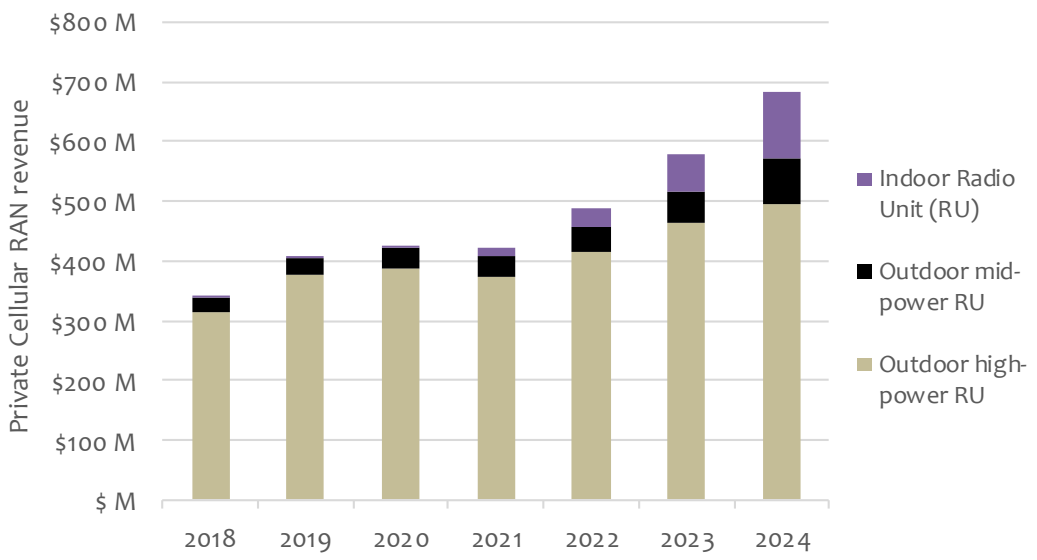
In large industries such as Oil & Gas, Mining, and others, network connectivity constitutes a very small portion of a company's capital expenditure. While many large industrial companies spend billions of dollars on automation, most of the expenditure falls in the software applications and professional services aspects. As many large industry segments are serviced through global solutions companies like ABB, Siemens, Honeywell, General Electric, etc., there is a large Services component to many projects including those involving network solutions. We expect the Services revenue to match that of the equipment sales in Private LTE market.



Source: Mobile Experts

Chart 5: Private Cellular Revenue Share, Network vs. Devices vs. Services

In terms of equipment sales, the Radio Access Network comprised of both macro and small cells will make up for the largest portion, followed by end devices including customer premise equipment (CPE) and IoT devices. The transport network including IP/MPLS, microwave backhaul, etc. will also constitute a major portion of network equipment sales. While making up for the smallest portion of the overall network spend, Core EPC and Mobile Edge Compute (MEC) components will make an increasing share as some industrial applications look to distributed MEC facilities to handle certain latency-sensitive applications on site.



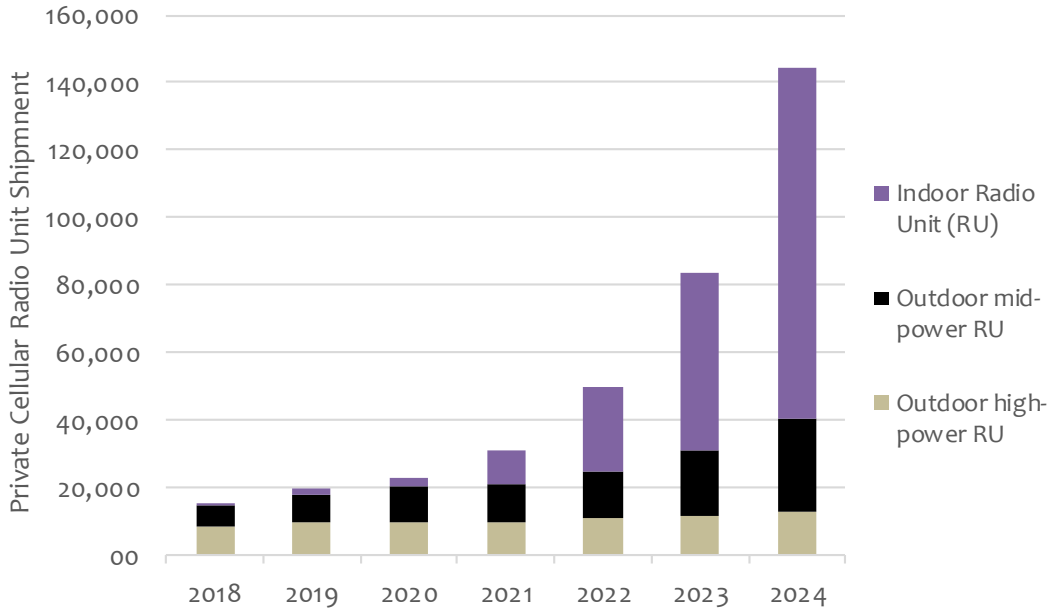
Source: Mobile Experts

Chart 6: Private Cellular Radio Access Revenue Share by Indoor vs. Outdoor

Regarding the Private LTE radio access market revenue, the majority of the RAN market will be attributed to Macrocell radios with composite power above 40W (Outdoor High-Power Radio Units). While there will be many outdoor small cells with composite power between 300mW – 40W (Outdoor Mid-Power Radio Units) used in Private LTE networks, the market value will be the only 1/10th of the Macrocells. As the private LTE adoption increases in indoor contexts in Manufacturing and Transportation venue deployments, the indoor small cells with composite power less than 300 mW per antenna (Indoor Low-Power Radio Units) will make an increasing portion of the total RAN market. During our forecast period, however, that portion will be relatively small (about $110M in 2024) since each Indoor RU has significantly lower ASP than the outdoor units.

Private LTE Radio Access and Device Shipment Forecast

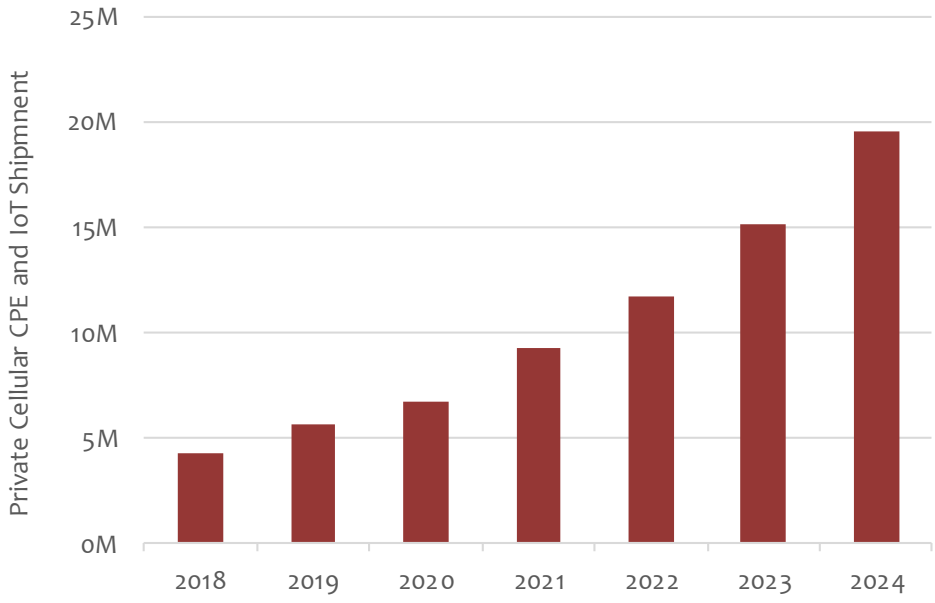
The near-term Private LTE market will be dominated by large projects in Oil & Gas, Mining, Public Safety, and Railway projects which require very broad coverage. For these large coverage-driven projects, Macrocells or High-Power Outdoor RUs would be the most economical means to provide coverage. As the number of Private LTE projects in other sectors such as airport hub and shipping port deployments increases, the number of small cell shipments will increase dramatically. Then, we expect the Manufacturing and warehousing sector adopt Private 5G in the latter years of our forecast period.



Source: Mobile Experts

Chart 7: Private Cellular Radio Unit Shipments, 2018-2024

The number of Private LTE devices including CPEs and IoT devices will steadily increase rising from less than 5M units in 2018 to almost 20M in 2024. The utility meters and CPE and IoT sensors in Manufacturing will dominate the shipment counts during our forecast period.

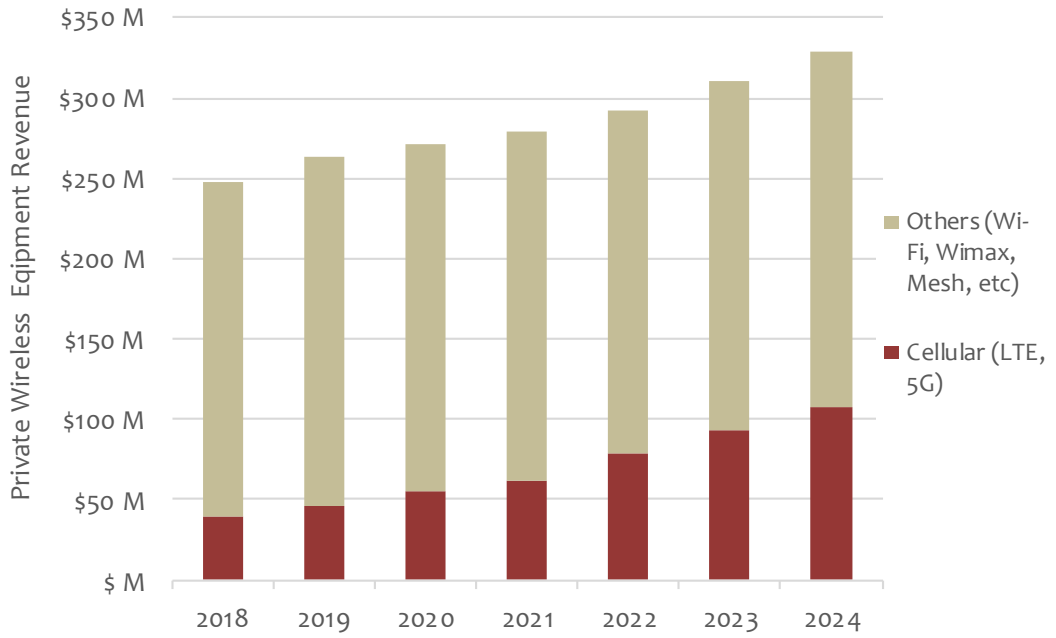


Source: Mobile Experts

Chart 8: Private Cellular CPE and IoT Device Shipments, 2018-2024

Private LTE Forecast in Oil & Gas

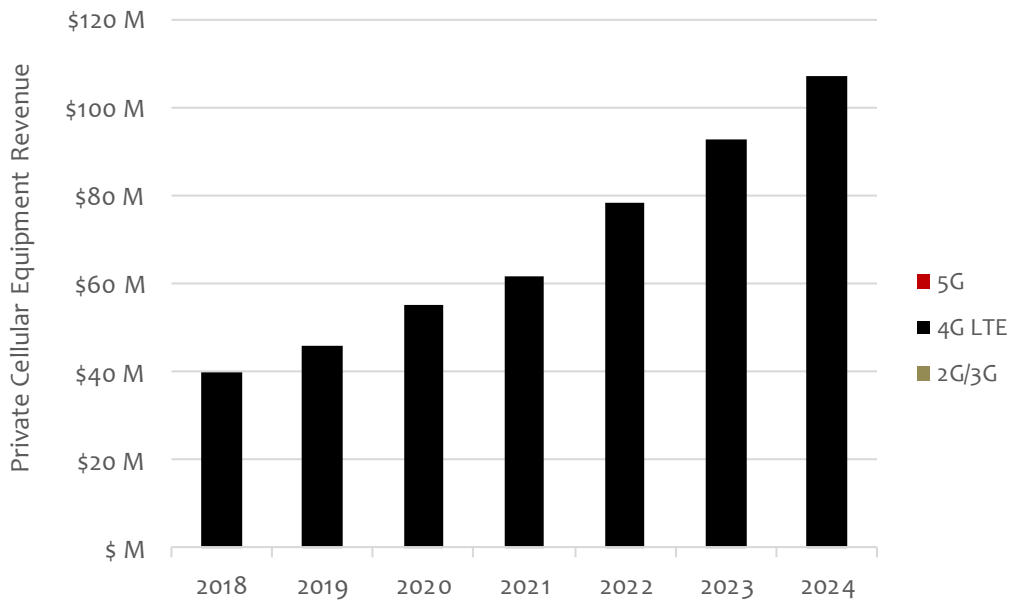
The Oil & Gas industry is dominated by very large global players with onshore and offshore oil fields in multiple countries with different regulatory and political environments. So, they are accustomed to working in diverse business settings. When it comes to network technology adoption, they have worked with a diverse set of wireless technologies and spectrum to solve their operational challenges. Often, this involves system integrators and automation experts like Siemens, ABB, and other industrial systems operators bringing the best solution forward. There is a large installed base of Wimax and industrial WLAN systems for offshore and onshore oil fields--but the number of new projects and large oil fields coming up for network upgrades is expected to be a few in numbers (20-30 in our forecast). Of these opportunities each year, an increasing share of projects will be won by Private LTE systems as spectrum availability through leasing, dedicated spectrum for industrial use, and CBRS in the USA become more widespread especially in the second half of the forecast period.



Source: Mobile Experts

Chart 9: Private Cellular vs. Other Wireless in Oil & Gas, 2018-2024

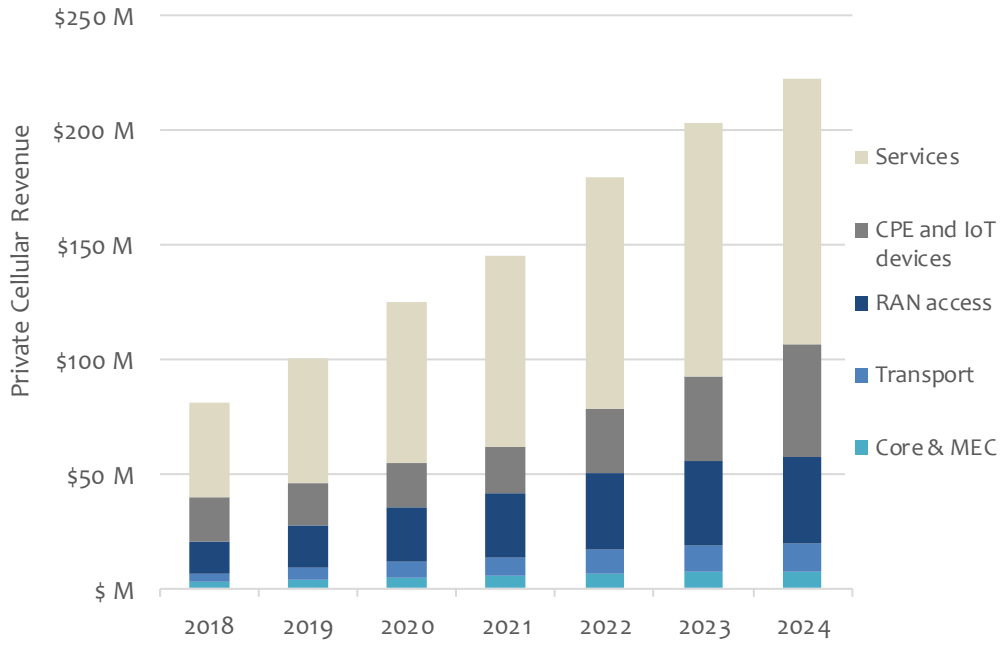
Despite the long sales cycles and long lifespan of existing wireless systems, Private LTE/5G share of the overall private wireless expenditure will double from less than $50M today to over $100M in 2024.



Source: Mobile Experts

Chart 10: Private Cellular Equipment Revenue by Technology in Oil & Gas, 2018-2024

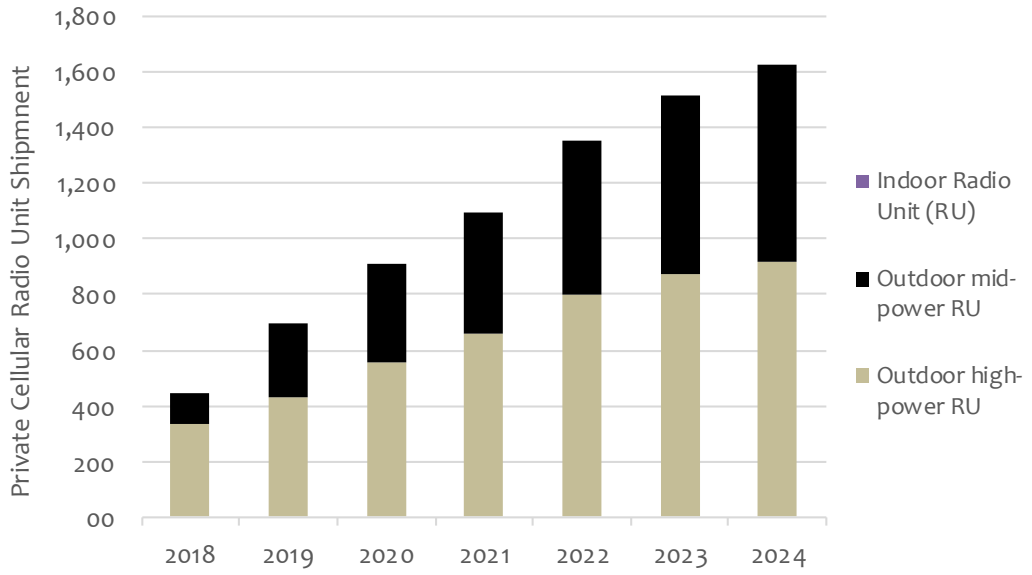
LTE can meet myriad application needs in Oil & Gas including wireless data transmission for offshore facilities, gas or oil pipeline monitoring through process instrumentation, and asset tracking or video surveillance. We expect the majority of Oil & Gas wireless requirements can be satisfied with LTE; hence, all of the private Oil & Gas deployments will use LTE.



Source: Mobile Experts

Chart 11: Private Cellular Revenue by Equipment and Services in Oil & Gas, 2018-2024

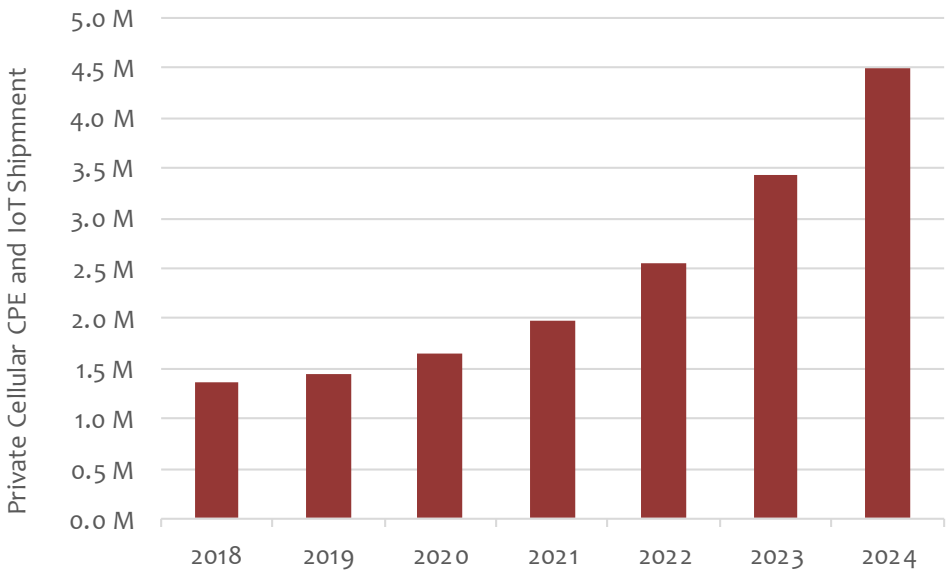
Breaking down the O&G Private LTE market opportunity by equipment type and services, the biggest portion of the opportunity will be in Services. Network equipment and deployment will involve meeting industry approvals regarding health, safety, security, and environmental concerns that have been standardized in the ATEX, FM, IECEx, and UL HazLoc standards. Private LTE network equipment including RAN (macro and small cells), Core (EPC and Edge Compute), and Transport (IP switches, routers, fiber, etc.) will constitute a small portion but will increase, and more projects adopt LTE solutions as spectrum availability becomes more widespread. The Network equipment market for the Oil & Gas sector will rise to about $60M in 2024 while the broadband CPE and cellular IoT modules for pipeline monitoring will constitute about $50M. Including both equipment and services, the total private LTE revenue opportunity in the Oil & Gas sector will rise to about $220M in 2024 growing at about 18% CAGR.



Source: Mobile Experts

Chart 12: Private Cellular Radio Unit Shipment in Oil & Gas, 2018-2024

In terms of RAN shipment, High-power outdoor Radio Units (i.e., Macrocells) will dominate the Private LTE deployments in Oil & Gas. With large oil fields spanning tens of thousands of square miles, high-power radios are the most economical way to provide broad coverage. However, we also see the opportunistic deployment of 5-40W radios (Outdoor Mid-Power Radio Units) for spot coverage and capacity in strategic field offices.



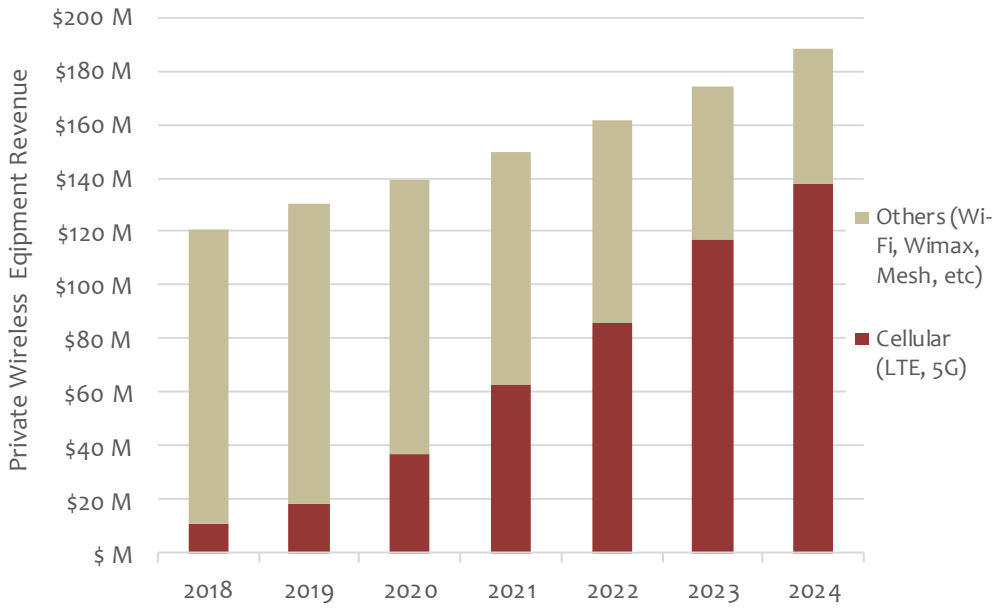
Source: Mobile Experts

Chart 13: Private Cellular CPE and IoT Device Shipment in Oil & Gas, 2018-2024

In addition to an increasing number of Private LTE deployments, we expect rising use of IoT devices for analyzing gas or oil pipeline process flow. As Oil & Gas companies continue their digitalization journey by optimizing their operations through digital communication of their assets and process flows, the IoT devices will continue to proliferate. The Private LTE end device shipments in the Oil & Gas sector will rise from under 1.5M in 2018 to about 4.5M in 2024.

Private LTE/5G Forecast in Mining

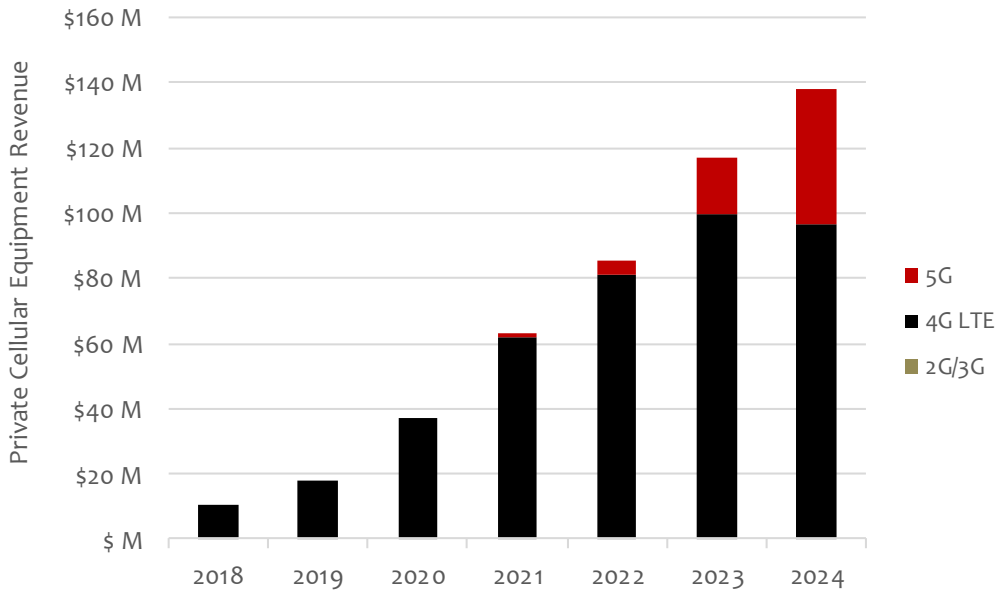
Compared to the Oil & Gas industry, Mining is ramping up its digital transformation more broadly. As the full autonomy characterized by remote-controlled drills and hauling trucks ramp up, we expect more surface mine operations to transition towards Private LTE. Rio Tinto's early work in full autonomy is expanding, and other mining companies are already working on plans to follow suit. While the Private LTE adoption in the Mining sector is in early stages, Mobile Experts forecasts a quick ramp-up growing at 50% CAGR to about $140M in 2024. The news about Komatsu's LTE-capable hauling trucks is a good indicator of the market adopting LTE as the more predictable private wireless system is needed to support real-time aspects of full autonomy.



Source: Mobile Experts

Chart 14: Private Cellular vs. Other Wireless in Mining, 2018-2024

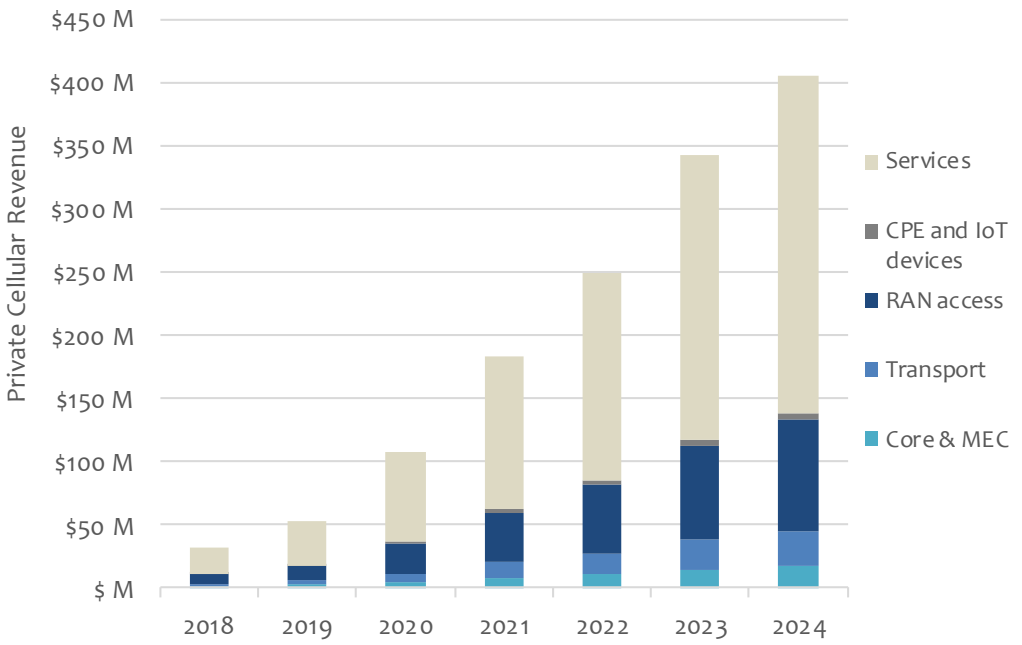
The Private Cellular share of the overall private wireless expenditure in the Mining sector will grow from less than 10% in 2018 to 70% in 2024. With the success of full autonomy taking root at major mining companies, the Private Cellular share can potentially increase significantly higher and grow the private wireless market overall. We expect "Other" wireless technologies such as Wi-Fi mesh to remain share in smaller mining operations for many years to come.



Source: Mobile Experts

Chart 15: Private Cellular Equipment Revenue by Technology in Mining, 2018-2024

With increasing adoption of digital transformation beyond full autonomy of hauling trucks into other heavy equipment, Mobile Experts believes 5G adoption will increase as technology and product maturity takes hold in the second half of the forecast period. In the near term, LTE will provide predictable broadband connectivity that is necessary for the initial use cases of full autonomy such as remote-controlled heavy equipment.



Source: Mobile Experts

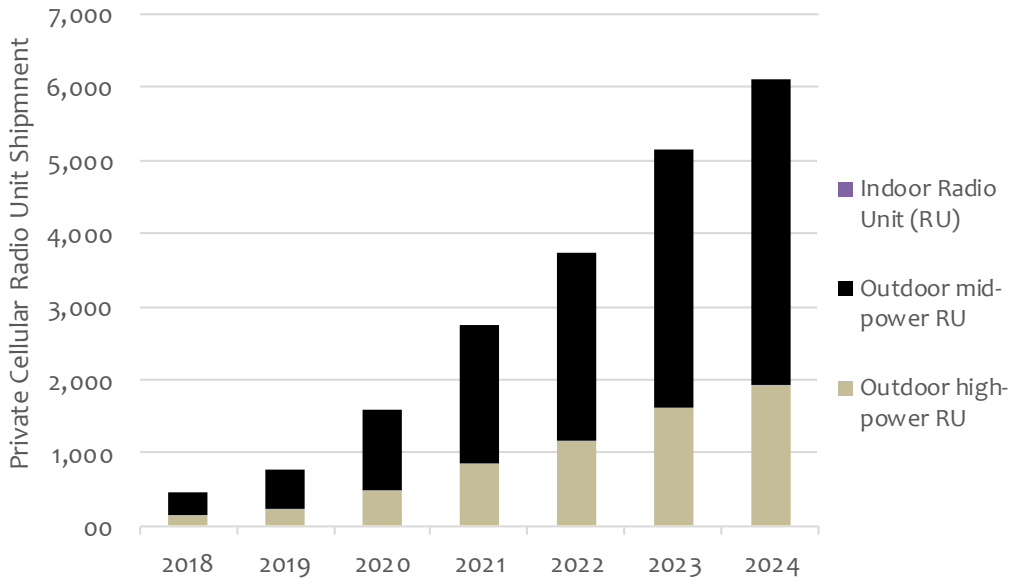
Chart 16: Private Cellular Revenue by Equipment and Services in Mining, 2018-2024

Similar to the Oil & Gas industry, the Services component will constitute the largest segment of the Private LTE market opportunity in the Mining sector. Industry-specific health, safety, security, and environmental considerations must be factored into product approval and installation processes. The combined Private Cellular network equipment including RAN (macro and lots of outdoor small cells), Core (EPC and Edge Compute), and Transport (IP switches, routers, fiber, etc.) will rise to over $130M in 2024. While the number of mines adopting Private LTE/5G is expected to be higher than the number of Oil & Gas fields, the number of RAN access nodes is expected to be lower in the count. For example, a single Macrocell may be sufficient for coverage of a surface mine with several outdoor small cells for capacity expansion.

Meanwhile, the CPE and cellular IoT modules for mining are expected to be minimal initially as the number of CPEs associated with heavy equipment will be in teens. For example, Rio Tinto operates 650 trucks, drills, and locomotives over 16 mines in one particular region.[11] While Mobile Experts expects the number of cellular IoT devices per mine to increase over time, the near-term adoption will be limited to a few use cases such as environmental

[11] Rio Tinto 2018 investor presentation

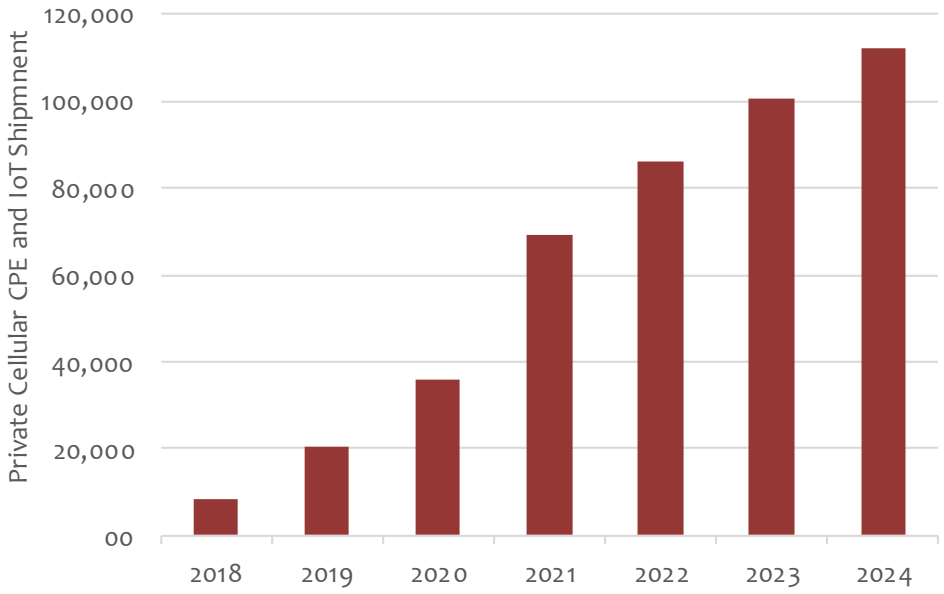
sensing in an underground mine for safety. Hence, the revenue contribution from end devices is forecasted to be limited in the near term – rising from a small base to about $5M in 2024.



Source: Mobile Experts

Chart 17: Private Cellular Radio Unit Shipment in Mining, 2018-2024

With the increasing number of mines adopting Private LTE today, Mobile Experts forecasts an increasing number of both outdoor small cells (Outdoor mid-power RUs) and Macrocells (Outdoor High-Power RUs). In our forecast, we have modeled about 7-8x more radio nodes per surface mine vs. underground mine to account for a larger coverage footprint for remote-controlled automation of heavy equipment. For underground mines, we have modeled more outdoor small cells being deployed for communication and IoT sensing coverage footprint.



Source: Mobile Experts

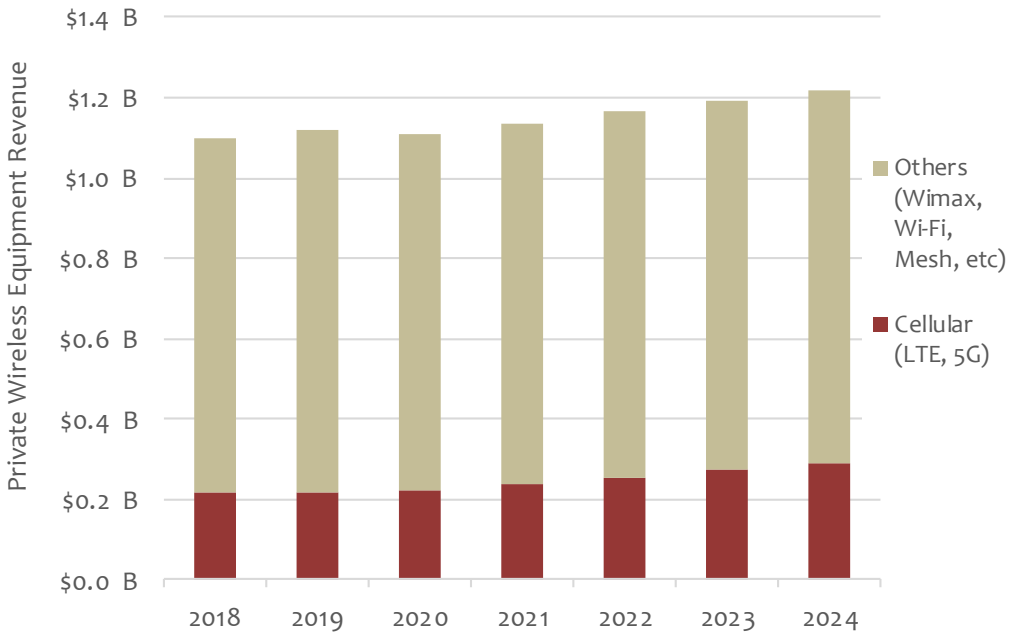
Chart 18: Private Cellular CPE and IoT Device Shipment in Mining, 2018-2024

Based on Rio Tinto's full autonomous operation in Australia, we have assumed about 40 CPE devices for heavy equipment under automation control and additional 250-500 cellular IoT devices for each mine. The number of IoT devices was over-indexed towards underground mines as we expect mining companies to put a lot more sensor devices to monitor health, safety, and environment-related aspects of mining operations.

Private LTE Forecast in Utilities

According to the Edison Electric Institute, a trade association that represents all US investor-owned utility (IOU) companies, and major international utilities and suppliers, the annual capital expenditure for the industry has exceeded $110B in the last couple of years. The capital expenditure in the *Distribution* segment, which represents the electricity delivered from substations near population centers to residential and business consumers, has roughly represented about 29-30%.[12] Mobile Experts estimates that the utilities spend less than 5% of this *Distribution* CAPEX ($15B per year) on a communications network including wired and wireless infrastructure, meters, and associated services with wireless networking representing less than half of the communications network spend. With legacy communications networks based on MAS (RF meshing technology on 900MHz band) still in use, Mobile Experts forecasts a very gradual adoption of Private LTE systems. Utilities typically view lifecycle of communication networks in decades, so the number of system upgrades is expected to be few. Government-directed smart grid projects in China and other regions and broadband upgrade onto new spectrum bands in 400 MHz and 4.9 GHz will provide some tailwind to the Private LTE spend moving forward.

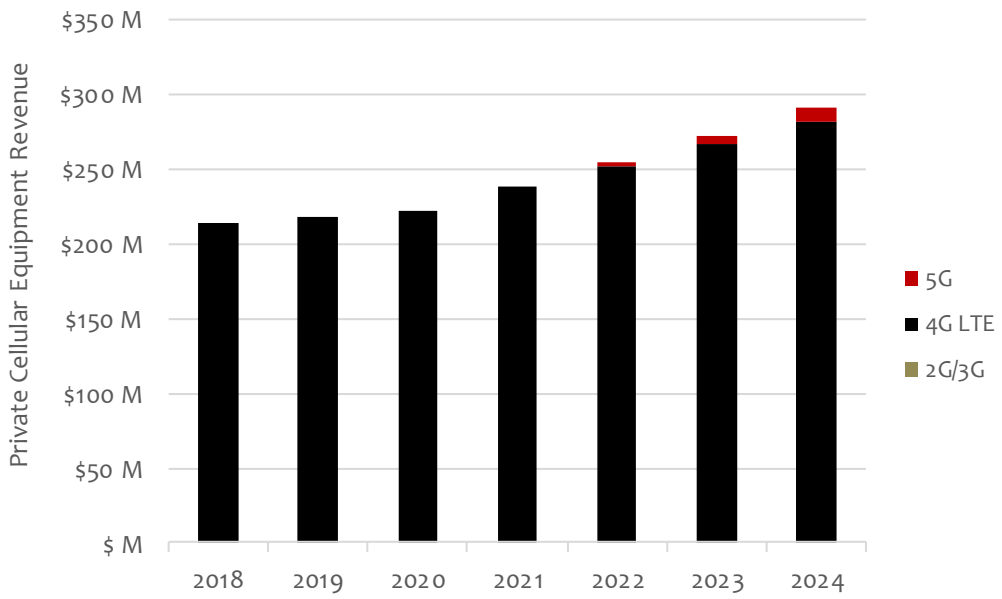
[12] EEI industry capital expenditure with functional detail (October 2018)



Source: Mobile Experts

Chart 19: Private Cellular vs. Other Wireless in Utility, 2018-2024

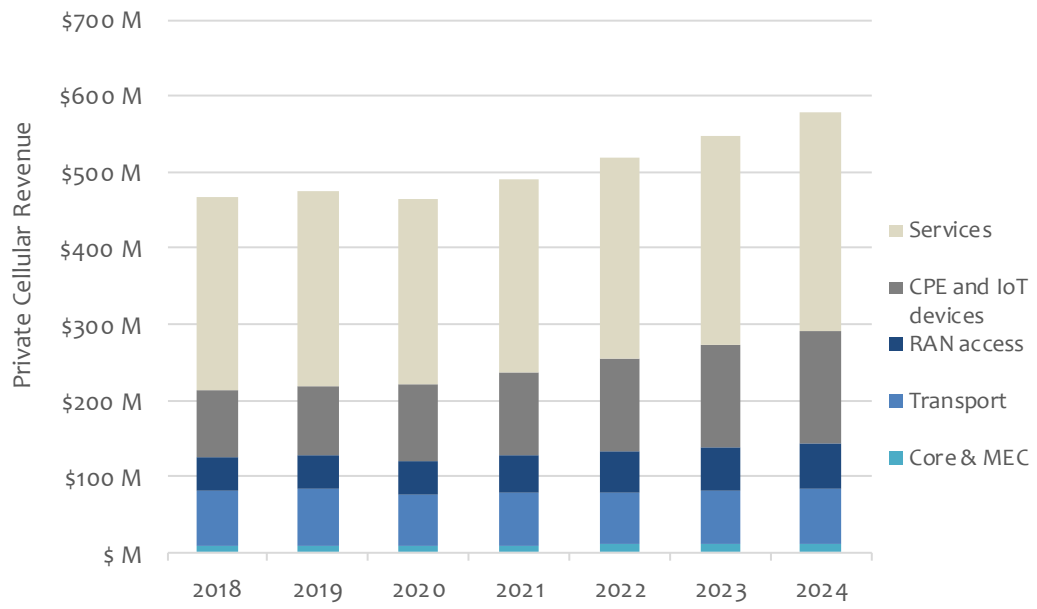
The Private Cellular share of the overall private wireless expenditure in the Utility sector is forecasted to remain fairly steady around $200-300M. Although our forecast shows a steady market, the actual sales may be lumpy as major smart grid initiatives may skew a year-over-year trend. In general, however, the utilities are expected to leverage Private LTE in certain markets where metering on owned or leased spectrum using LTE provides more predictability and assurance instead of AMI metering on "congested" unlicensed spectrum.



Source: Mobile Experts

Chart 20: Private Cellular Equipment Revenue by Technology in Utility, 2018-2024

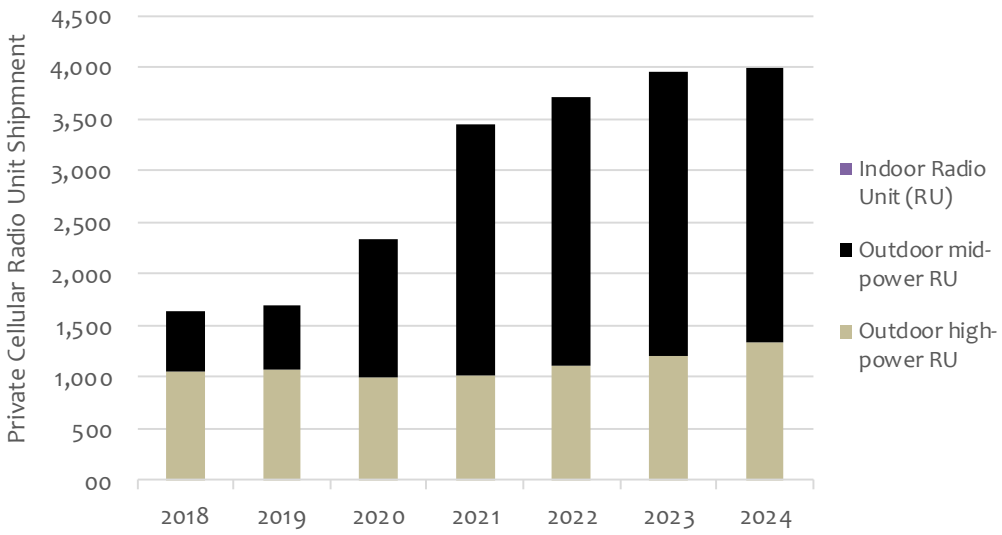
Mobile Experts believes that the majority of smart grid projects leveraging Private LTE systems will focus on efficient use of energy consumption through smart street lighting, operational efficiency through smart metering and fault monitoring. While there are several interesting 5G use cases being trialed today, such as VirtuWind project to investigate wind farm optimization through SDN and NFV control infrastructure, and the WIVE project in Finland to investigate the impact of 5G ultra reliable low latency communications (URLLC) on smart grid applications, Mobile Experts believes the "real-world" 5G adoption in the Utility sector is several years away. The maturity of the 5G ecosystem and the benefits of expanding scale in terms of broad competitive offerings in the marketplace will require some time.



Source: Mobile Experts

Chart 21: Private Cellular Revenue by Equipment and Services in Utility, 2018-2024

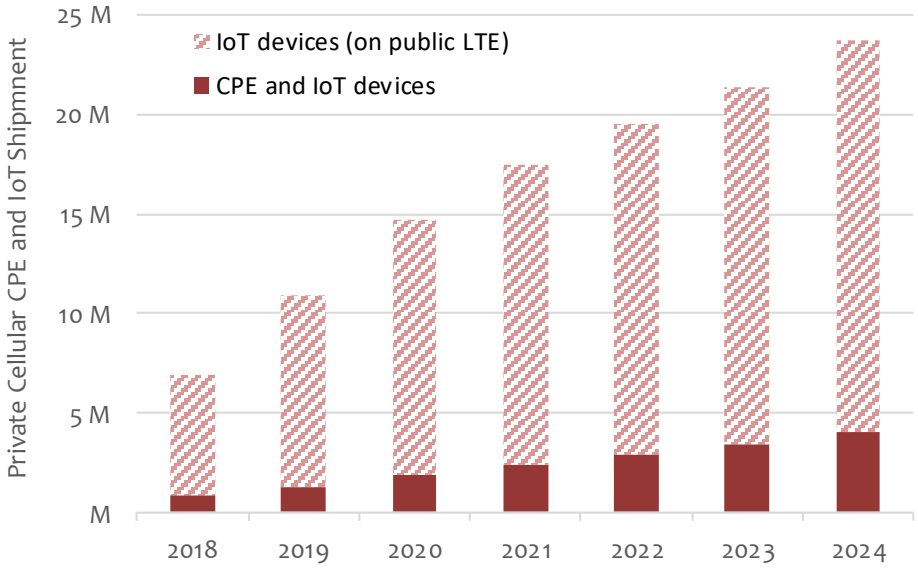
Again, the Services component will constitute the largest segment of the Private LTE market opportunity in the Utility sector. Unlike Oil & Gas and Mining, in Utilities the cellular IoT market will represent the largest share of the equipment revenue opportunity. While utilities prefer owning their own networks for smart grid application, Mobile Experts believes that some will leverage "public" cellular RAN infrastructure with a "slice" of spectrum or bandwidth dedicated for smart grid applications. Even though the majority of cellular IoT devices for utility metering will be on the "public" cellular networks, the private portion, i.e., those running on private LTE, will still make up almost half of the private LTE equipment sales in 2024.



Source: Mobile Experts

Chart 22: Private Cellular Radio Unit Shipment in Utility, 2018-2024

While the majority of Private LTE networks operating in 400 – 900 MHz will leverage High-power Outdoor Radio Units (i.e., Macrocells), Mobile Experts believes that some legacy Wimax networks operating in the legacy 3.65 GHz band will migrate over to LTE starting in 2020 as their grandfathered exemption status expires in the first half of 2020 as per the CBRS (FCC Part 96) rule. There is a possibility that the timeline may change, in which case, our forecast of the Outdoor small cells (Mid-power RUs) ramp will likely be delayed by a year.



Source: Mobile Experts

Chart 23: Private Cellular CPE and IoT Device Shipment in Utility, 2018-2024

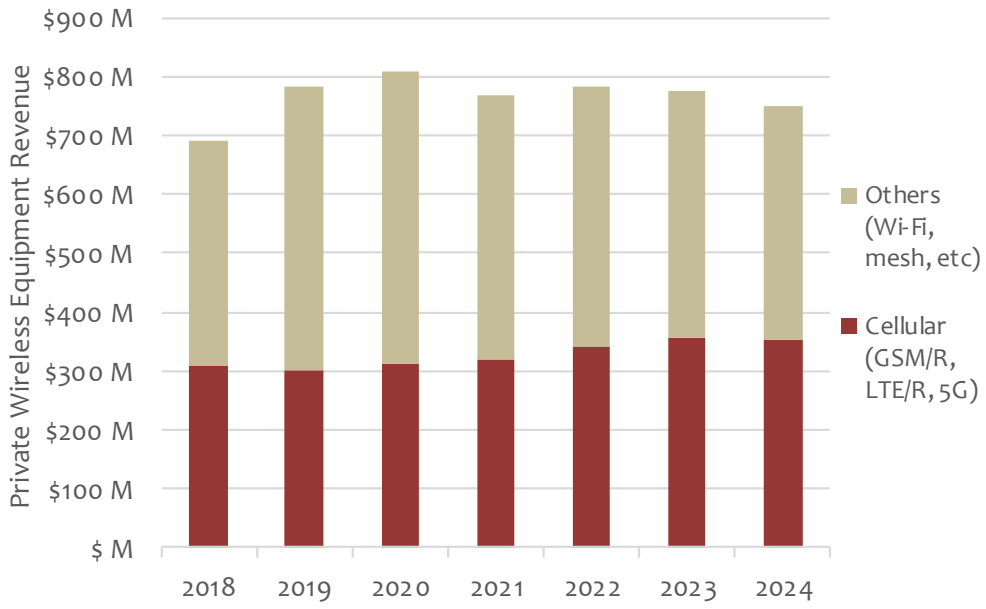
As illustrated above, Mobile Experts believes that a big share of utility metering application may run off of "public" LTE and 5G networks leveraging massive IoT features.

Private Cellular Forecast in Transportation

The Private Cellular forecast in the Transportation sector is based on three key use cases:

1. Airport communication and automation;
2. Shipping port automation; and
3. Railway communications networks

While there are many promising Private LTE use cases at major transportation hubs such as airports and shipping ports ranging from operational communication, video surveillance for security, and automation of port operations, Mobile Experts believes that the bulk of Private Cellular opportunities can be found in railway communication projects in the near term. Since the last major GSM-R specification released in 2010, there have been several GSM-R upgrades and GSM-R system expansion in Europe, China, India, and Australia. Moreover, the LTE-R project announced in Korea is likely to continue the expanding railway communication projects numbering in thousands of "macro" base stations over the next several years. Based on the number of GSM-R and LTE-R project announcements, Mobile Experts forecasts the private cellular (including GSM-R, LTE-R, and traditional LTE and 5G network deployments at airports, train stations, shipping ports) market will be comprised of $200-300M average annual equipment sales for the railway applications and $50-$100M in airport and shipping port applications.

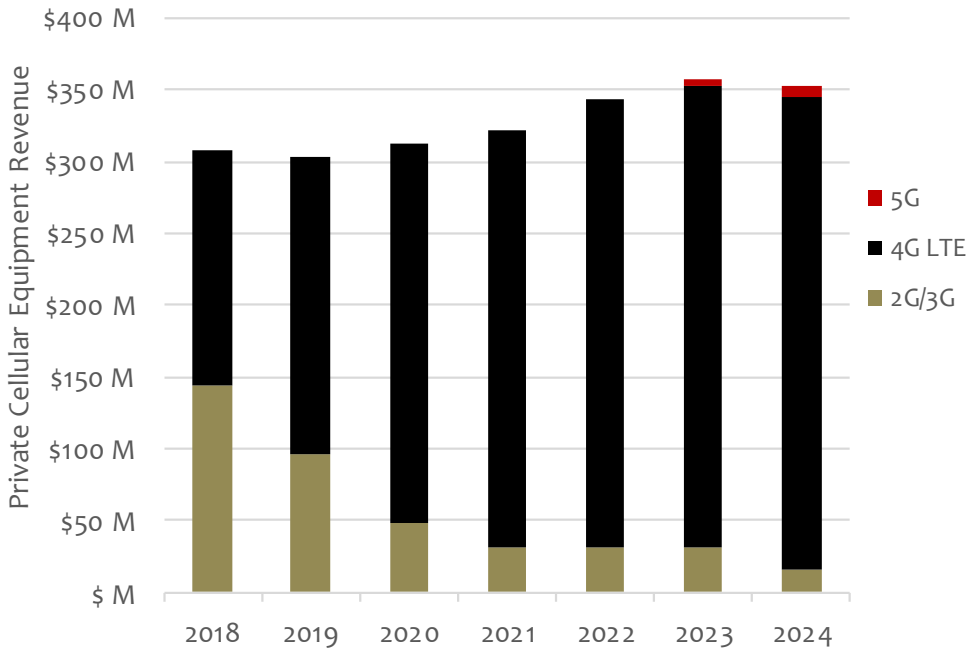


Source: Mobile Experts

Chart 24: Private Cellular vs. Other Wireless in Transportation, 2018-2024

It should be noted that the "Other" alternative private wireless network market will mainly be comprised of Wi-Fi access points deployed at airports and train cars and proprietary point-to-point (PtP) and point-to-multipoint (PtMP) wireless networking gears for backhaul and transport of high-bandwidth applications like video surveillance that shipping ports utilize today.

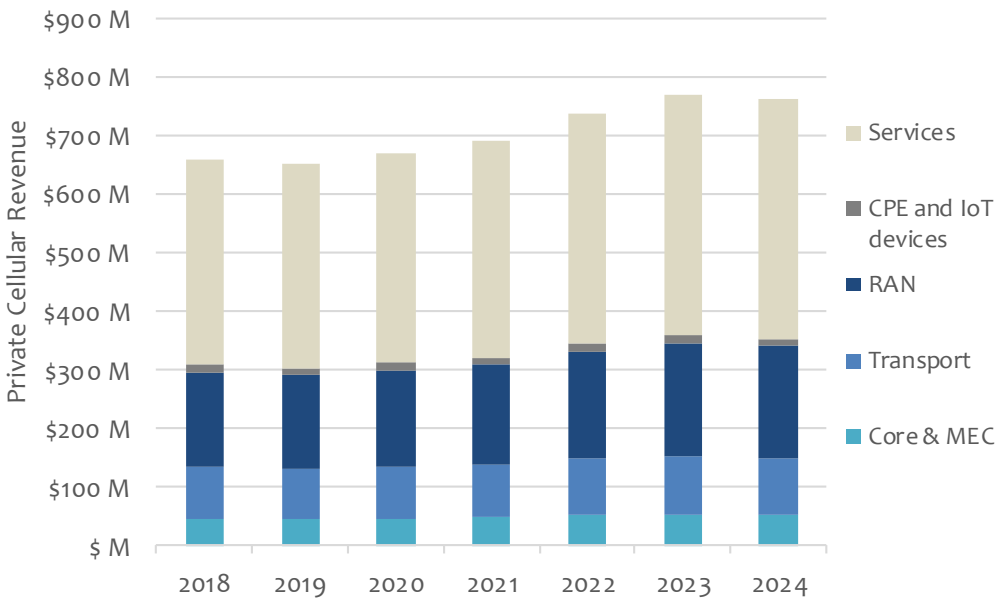
We should note that commercial telematics and fleet management use case was considered as part of the Transportation sector. Mobile Experts believes that this particular segment within the Transportation industry leverages operators' "public" cellular networks; hence, we do not expect any private LTE networks to be deployed directly by the enterprises in this industry. There are millions of commercial fleet vehicles, and Mobile Experts forecasts tens of millions of cellular IoT devices being shipped during the forecast period. However, these "public" LTE equipment sales are not reflected in our forecast below.



Source: Mobile Experts

Chart 25: Private Cellular Equipment Revenue by Technology in Transportation, 2018-2024

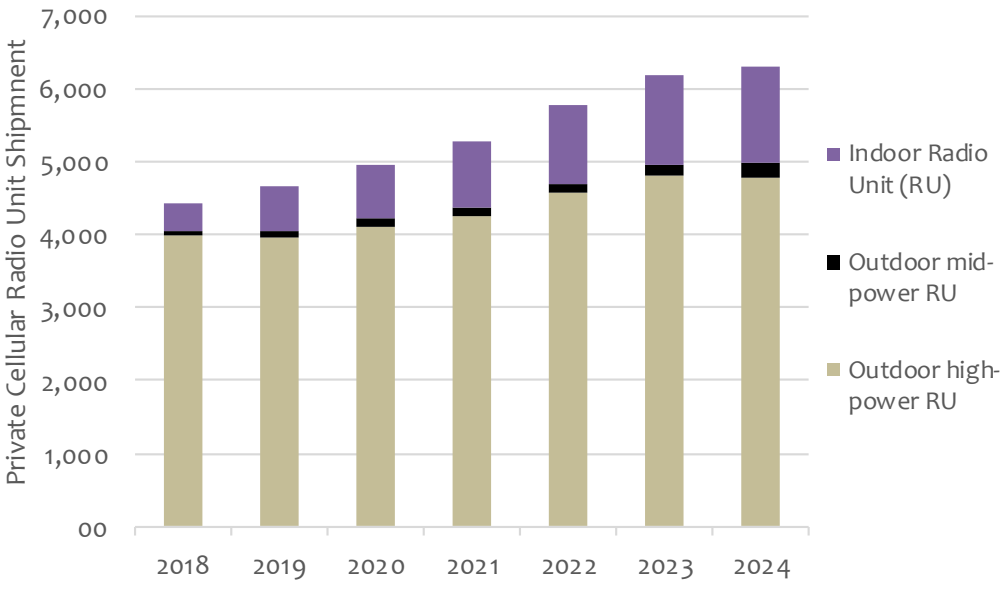
Mobile Experts believes that the majority of private cellular applications at airports, shipping ports and railways largely focused on high-bandwidth broadband applications can be addressed through LTE (including LTE-R) technology. While we envision industrial automation efficiencies can be achieved through 5G URLLC and massive IoT features in this sector (e.g., crane automation at shipping ports, high-speed railway safety operations, etc.), Mobile Experts expects the real-world adoption for 5G features will be limited in the near term.



Source: Mobile Experts

Chart 26: Private Cellular Revenue by Equipment and Services in Transportation, 2018-2024

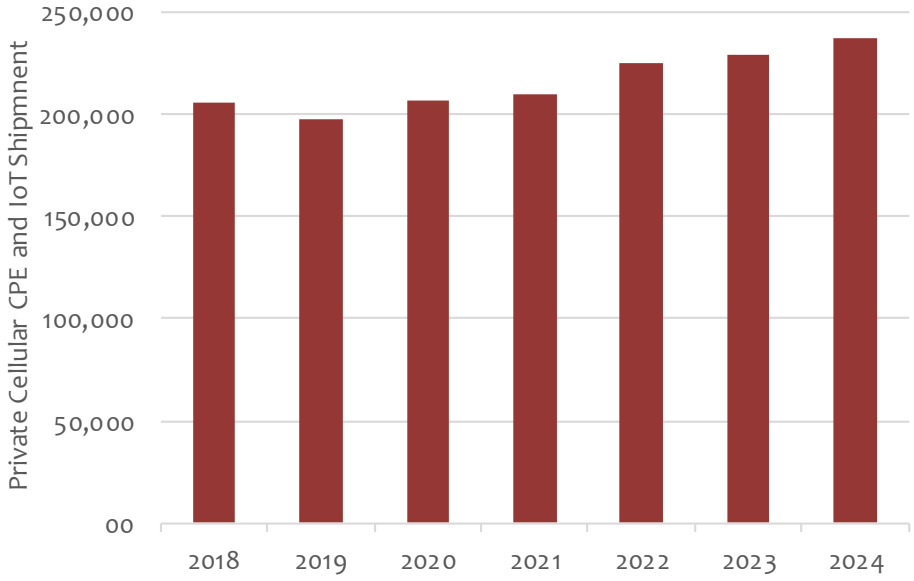
Like other large industrial sectors with regulatory and safety standards to consider, the Services component constitutes the largest segment of the Private LTE market opportunity in the Transportation sector. The RAN portion, especially Macrocell tower investments for railway applications, will make up for the largest share of the network equipment sales. The Transport segment-- including IP/optical transport for the Macro radios along railroad tracks - will constitute a big portion as well.



Source: Mobile Experts

Chart 27: Private Cellular Radio Unit Shipment in Transportation, 2018-2024

In terms of RAN shipment, High-power outdoor Radio Units (i.e., Macrocells) will dominate the Private Cellular deployments in Transportation from GSM-R and LTE-R railway projects. A big portion of that is expected from the LTE-R deployment in Korea that covers 4800 km of railroad routes. We are forecasting that additional 10,000 km of railway routes will be covered through either GSM-R or an LTE-R variant over the next eight years. While the actual capital spending in these large projects may vary significantly from one year to the next, our model assumes average spending that is increasing due to the expansion of railway projects in more countries over the next several years. The outdoor (Outdoor Mid-Power RU) and indoor small cell (Indoor RU) shipments are mostly from airport and shipping port use cases where these provide network coverage within venues and extended outdoor areas. We have taken a conservative adoption of Private LTE systems at airport and shipping port use cases, as many of these venues are already addressed through PtP and PtMP and Wi-Fi systems. We see the benefits of Private LTE to take hold eventually, but the rate of adoption may be slower than most forecasters expect.



Source: Mobile Experts

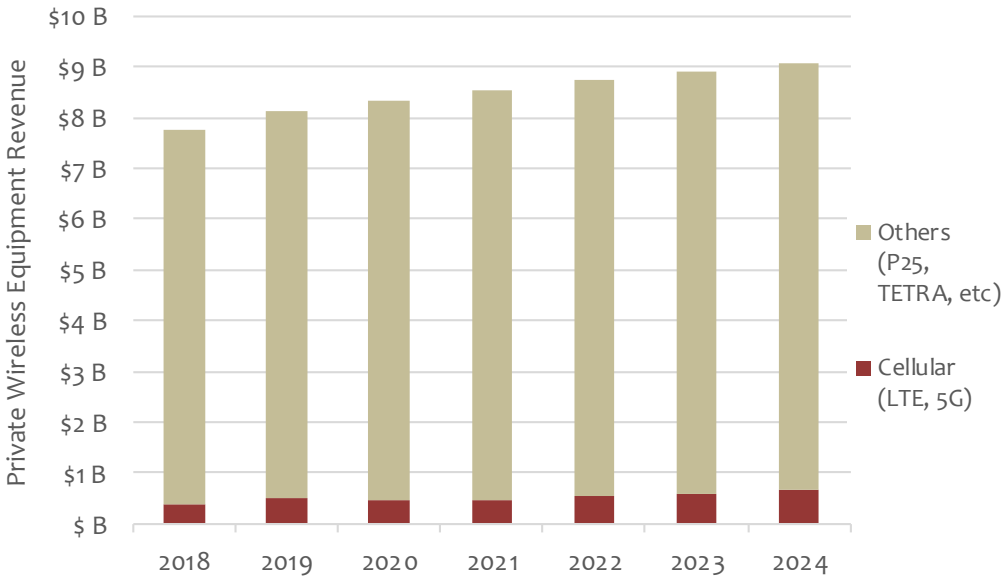
Chart 28: Private Cellular CPE and IoT Device Shipment in Transportation, 2018-2024

Compared to other sectors, Mobile Experts forecasts the unit shipment of end devices comprised of CPE units on trains for broadband connectivity and cellular IoT devices for automation control will be somewhat limited, which is largely based on our view that the number of airport and shipping port adoption of Private Cellular systems will be a steady increase rather than geometric adoption growth.

Private Cellular Forecast in Government (Public Safety, Military)

The Private LTE adoption in the Government sector is primarily coming from the migration of two-way public safety radio systems like P25, TETRA to LTE broadband systems often noted as Public Safety LTE (PS-LTE), and military applications such as "on-the-go" private wireless networks for tactical radio communication. While

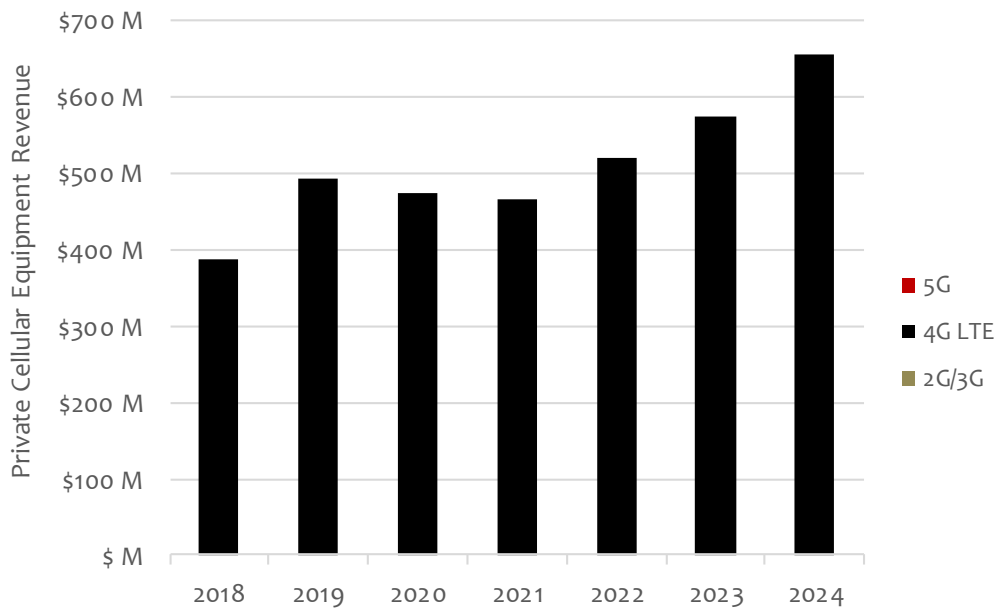
It should be noted that our forecast only counts dedicated private PS-LTE systems. For instance, the FirstNet network investment in the USA is not counted in our forecast below since the Band 14 network investment (on AT&T network) is shared with "public" consumer mobile broadband service when the Band 14 capacity is not used by public safety personnel. This type of "shared" PS-LTE arrangements are considered "public" network investment thus not reflected in our Private LTE equipment sales below. On the other hand, we do count the Band 14 public safety LTE devices used by first responders in our forecast.



Source: Mobile Experts

Chart 29: Private LTE vs. Other Wireless in Government, 2018-2024

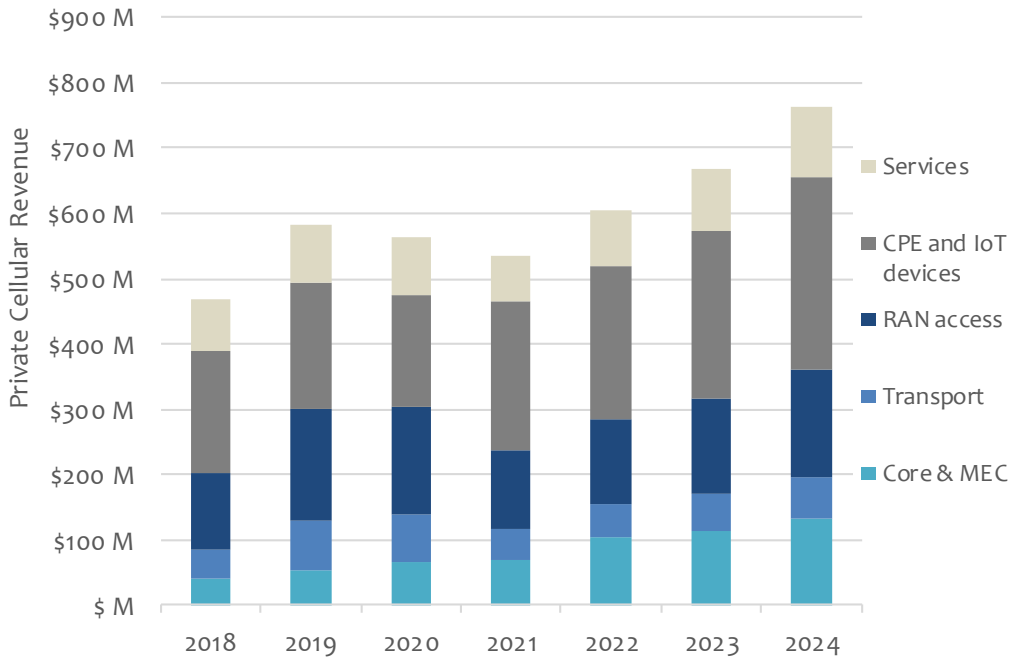
While PS-LTE has been implemented in some countries already and is being deployed in others, the majority of Public Safety and military equipment sales are based on legacy systems. By our estimate, the legacy Land Mobile Radio equipment market that dominates the Public Safety sector is expected to maintain its dominant share at $6-7B annually. The Private LTE share is expected to take share, especially as FirstNet deployment creates a tailwind for PS-LTE user devices during the forecast period. However, the Private LTE share of the overall Government sector will remain under 10%, with over $500M PS-LTE segment and over $100M military segment in 2024.



Source: Mobile Experts

Chart 30: Private Cellular Equipment Revenue by Technology in Government, 2018-2024

LTE is expected to dominate the Private LTE market for the majority of Public Safety and military applications. Thus, we don't foresee the government customers to actively seek 5G for their Private LTE applications during the next five years.

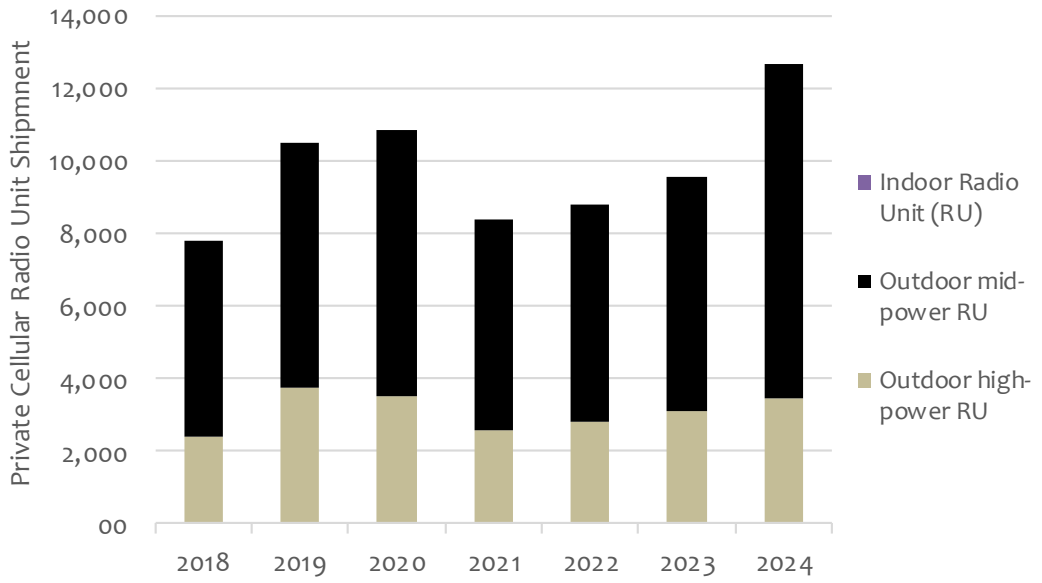


Source: Mobile Experts

Chart 31: Private Cellular Revenue by Equipment and Services in Government, 2018-2024

In the Government sector, specifically in the Public Safety segment, the PS-LTE adoption is somewhat lumpy as the major PS-LTE deployment on 1.4, and 1.8 GHz band in China has already come and gone. The near term (2018-2020) ramp is largely attributed to the PS-LTE deployment in Korea where the Korean government is expected to spend close to $900M for a nationwide PS-LTE on dedicated 700 MHz bands. Our forecast assumes that some PS-LTE trials that are on-going in Europe (Finland, France, etc.) would transition into wider deployments. The sales ramp in the second half of our forecast period is mainly attributed to PS-LTE terminal sales in the USA.

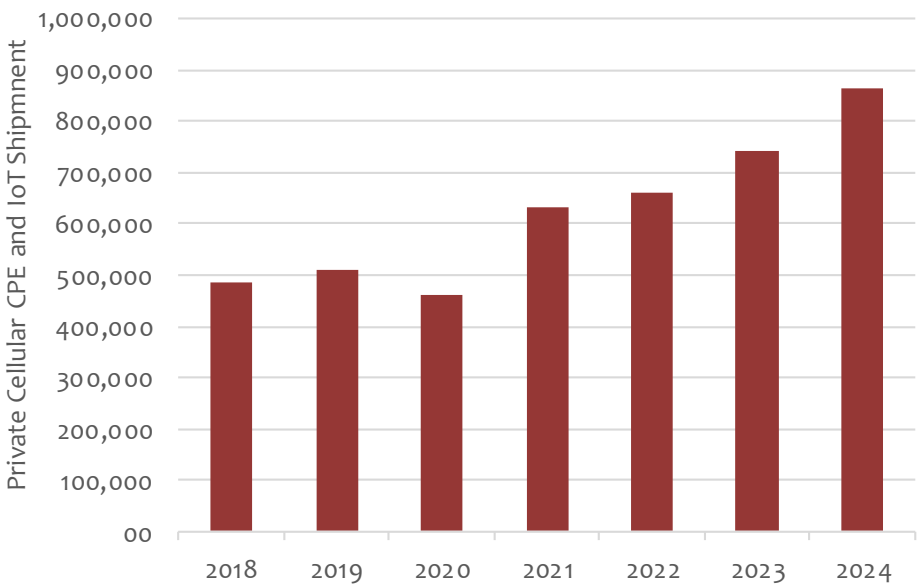
It should be noted that the Core and MEC segment is expected to garner higher value capture than other markets. The Core functions including self-organizing network (SON) capabilities are deemed much higher value functions--especially in military applications that require coordination of nomadic "base stations" to support tactical radio communication. Hence the Core/MEC function revenue increases over time corresponding to an increase in the number of military applications adopting Private LTE in the latter years.



Source: Mobile Experts

Chart 32: Private LTE Radio Unit Shipment in Government, 2018-2024

The unit shipments of High-Power Outdoor Radio Units (i.e., Macrocells) are attributed to PS-LTE networks. Meanwhile, the Outdoor Mid-Power Radio Units are mainly attributed to military applications that require a network of outdoor radios to provide both coverage and capacity in field deployments.



Source: Mobile Experts

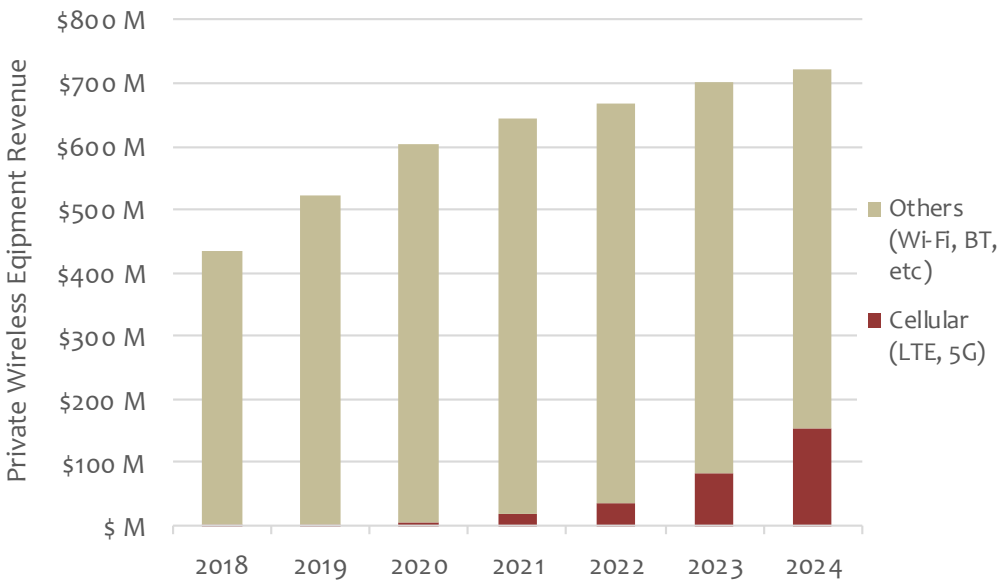
Chart 33: Private LTE CPE and IoT Device Shipment in Government, 2018-2024

The Private LTE end user device shipment is largely confined to user devices such as ruggedized LTE user devices for first responders including police, fire department, etc. and military personnel. The increasing "ramp" in 2021 is attributed to our expectation that more PS-LTE terminals will come to market as the FirstNet network adoption grows across different federal and state agencies.

Private LTE/5G Forecast in Manufacturing

The communication need in Manufacturing is mostly served through many variants of wired technologies (e.g., Industrial Ethernet and FieldBus). In some instances, wireless technologies like Wi-Fi and Bluetooth are used to facilitate reconfigurable operations on factory floors. According to HMS, wireless networking constituted about 6% of industrial communications market in 2018 and growing very quickly.[13] Mobile Experts estimates that the global industrial wireless networking market is roughly $350-400M today and will grow at 10% CAGR during our forecast period. As the 5G ecosystem matures and dedicated spectrums open up for industrial use, we believe many large manufacturers will quickly move to implement trial factories using Private LTE and 5G (with a preference for 5G of course). However, we believe the 5G industrial networking ecosystem will take a few years to mature. Hence, the Private LTE and 5G in Manufacturing will remain a small portion relative to alternatives which include 802.11ax during our forecast period.

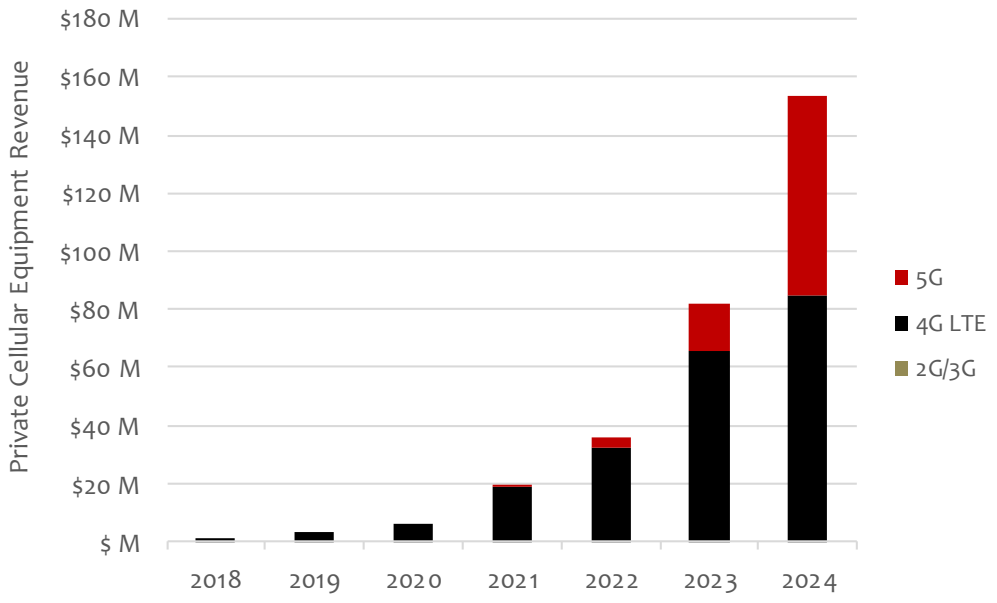
[13] HMS 2018 Industrial Communication Global Market Share



Source: Mobile Experts

Chart 34: Private LTE/5G vs. Other Wireless in Manufacturing, 2018-2024

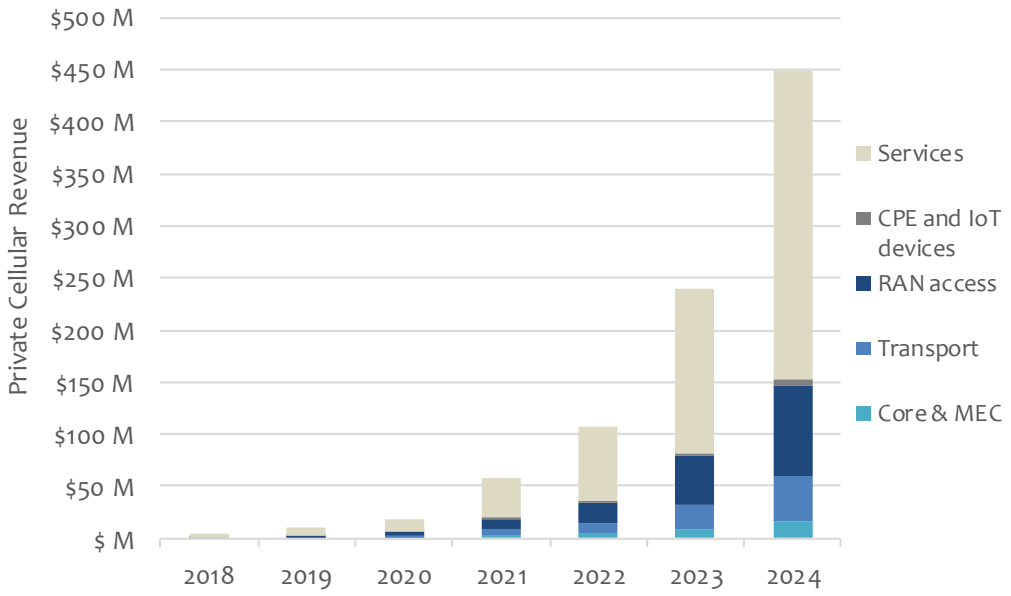
The Private Cellular share of the overall private wireless expenditure in the Manufacturing sector will grow quickly from less than 1% in 2019 to roughly 20% in 2024. Basic drivers include the higher reliability of LTE compared with Wi-Fi, as well as longer range (which can be translated as a superior link budget).



Source: Mobile Experts

Chart 35: Private Cellular Equipment Revenue by Technology in Manufacturing, 2018-2024

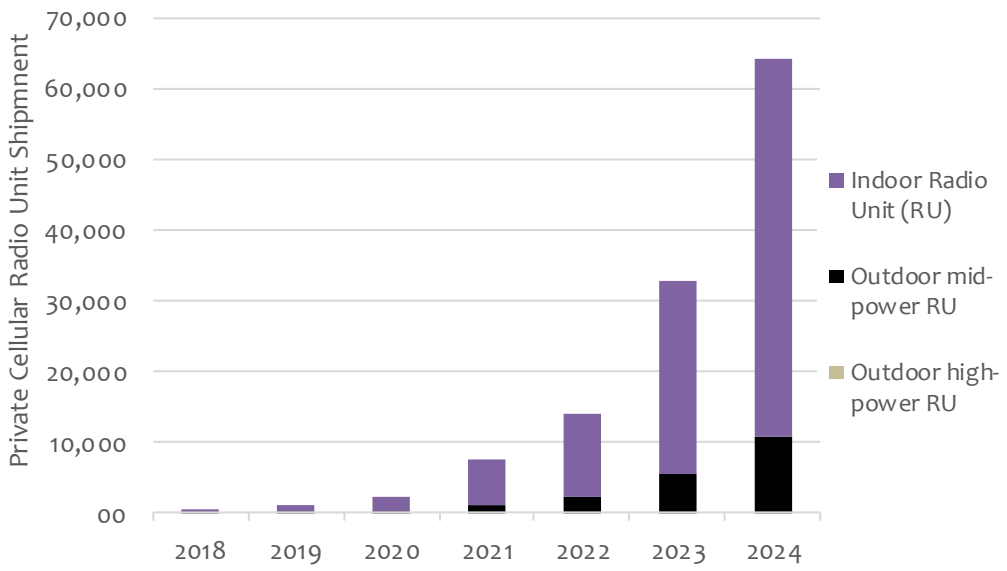
For smart factory application, 5G URLLC and massive IoT aspects will be most compelling for manufacturers looking for CAPEX reduction associated with cabling and more importantly the operational agility that wireless networking affords. While the initial smart factory application and trials will use LTE, several manufacturing companies will move to deploy initial 5G networks in the 2023-2024 timeframe.



Source: Mobile Experts

Chart 36: Private Cellular Revenue by Equipment and Services in Manufacturing, 2018-2024

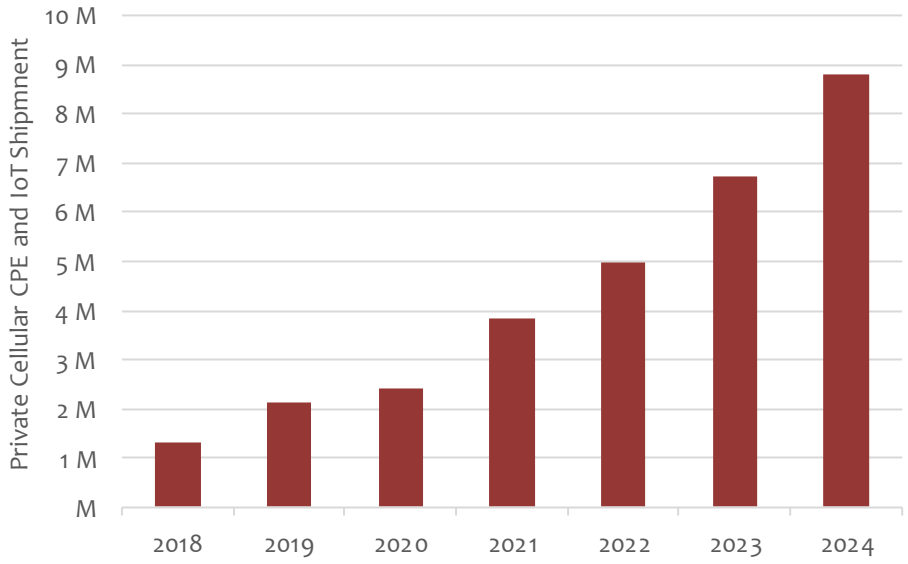
In the very early stages of Private LTE adoption in smart factory applications, the Services component will become a big part of revenue opportunity, but as the adoption scales to much higher levels (beyond our forecast period in our current view), the Services share of the overall opportunity will become smaller. Likewise, even though the cellular IoT devices make up a small portion in the early days, Mobile Experts expects the cellular IoT segment to become much larger after 2024, as manufacturers add large numbers of devices to automate complex process flows.



Source: Mobile Experts

Chart 37: Private LTE/5G Radio Unit Shipment in Manufacturing, 2018-2024

The bulk of Private LTE/5G radio access network in Manufacturing will be comprised of indoor units to provide high-density capacity coverage within factory floors. There will be some higher-power outdoor small cells (Outdoor Mid-Power RUs) to provide broader coverage in and around plants. For example, the new BMW plant in Shenyang, China is part of a multi-plant complex which we believe will require some outdoor small cells to provide coverage and capacity throughout the entire complex. For many large automotive plants, this is likely the case, and the need for both indoor and outdoor radio coverage is needed.



Source: Mobile Experts

Chart 38: Private LTE/5G CPE and IoT Device Shipment in Manufacturing, 2018-2024

With the increasing number of Private LTE/5G deployments in smart factories, we expect rising use of IoT devices for many aspects of factory automation ranging from production to environmental aspects to optimize energy use for example. In the new BMW Dadong plant, for example, energy savings through new building materials and intelligent lighting as well as water recycling are big drivers for the company's sustainable production goals.[14] Mobile Experts believes that the number of cellular IoT deployments in Manufacturing will likely grow exponentially especially as Private LTE/5G adoption scales in outer years.

[14] BMW Brilliance website (extracted January 2019)

7 COMPANY PROFILES

ABB

As a global automation company, ABB provides industrial automation solution to many industries. The company acquired Tropos back in 2012 to add to its wired and wireless communication network portfolio. ABB/Tropos' Wi-Fi meshing technology has been deployed in Utilities and other large infrastructure projects. One of the major projects for the firm includes a Smart Grid communication project for Kansas City Power & Light back in 2012. ABB offers Wi-Fi mesh radios using 2.4 and 5GHz unlicensed band, PtP and PtMP radios leveraging 900MHz unlicensed bands and 400 and 700MHz licensed bands.

AIRSPAN

Airspan is one of the leading LTE small cell vendors. The company has a range of LTE outdoor and indoor small cells and wireless backhaul products. While the company has found success with its LTE relay products at Tier 1 operators including at Sprint and Jio, it also addresses other sectors including wireless ISPs and vertical markets in Utilities, Public Safety, Transportation, and Oil & Gas. The company recently acquired Mimosa which has 802.11-based fixed wireless and backhaul products serving the wireless ISP market.

AMBRA

Ambra is a telecom engineering turnkey provider based in Canada. It owns licensed spectrum in Canada under its mobile operator brand, EcoTel with LTE footprint covering 6M sq.km. across the 700/850/1900/2500 MHz bands. It operates in the industrial, commercial, mining, and broadband services to remote communities. Solutions Ambra has carried out major projects for companies such as Agnico Eagle, ExxonMobil, Rio Tinto, ArcelorMittal, GoldCorp, Mine Canadian Malartic and Hydro-Québec, as well as for native communities in Northern Canada.

ALTIOSTAR

Altiostar provides virtualized, split-baseband RAN software solution that supports a wide range of indoor and outdoor radios including macros and small cells. The company has set up a proprietary baseband partition in which the scheduler sits in the radio head, allowing higher latency in the transport and much lower bandwidth for lower transport cost. The company has conducted several lab trials with few tier-one operators. The latest trial, and possibly network buildout, is with Rakuten in Japan where the former MVNO is in the process of building out own network to enhance its mobile business.

ATHONET

Athonet provides a software-based mobile core for voice and data networks that run in public & private clouds, or enterprise data center environments using standard commercial off-the-shelf hardware. The company developed its virtualized core network solution back in 2010 on VMware infrastructure. Most recently, the company partnered with Ambra in Canada's first underground private LTE network in the Agnico Eagle's LaRonde Mine in Quebec. Athonet provided virtualized EPC and IMS which provide critical communication voice and data services. The company has also partnered with AWS, Federated Wireless, and Ruckus to demonstrate running IoT applications on private LTE network running on CBRS band.

BOSCH

Bosch's Industrial Technology business unit houses factory automation and connected manufacturing solutions including customized drive, control, and linear motion solutions. Starting in 2018, the newly created Bosch Connected Industry business unit combines software development and projects related to Industry 4.0 that had previously been spread across different business groups within the company.

CAMBIUM NETWORKS

Cambium was formed in late 2011 after the original Motorola Canopy business was sold to private equity firm. Its PMP 450 platform has been widely deployed around the world, and the company provides both PtP and PtMP radio gears across a wide swath of spectrum bands including 900 MHz, 2.4 GHz, 3.65 GHz, and 5.9 GHz. The company's products are considered "carrier" class and used by WISPs and some industrial customers.

CASA SYSTEMS

Headquartered in Andover, MA, Casa Systems was founded in 2003 with core business in cable broadband and video product solutions. The company has since expanded its product solution portfolio to include wireless products addressing carrier Wi-Fi and small cell products. In addition, the company offers virtualized 4G/5G core gateway solution to complete the end-to-end solution offering for private LTE implementations. The company recently announced customer wins at China Mobile, Telefonica Spain, and Sprint for its small cell and small cell core gateway products.

CISCO

Cisco is a global leader in enterprise networking including WLAN. Cisco's wireless strategy is still largely focused around Wi-Fi and IEEE 802.11 roadmap offering Aironet class of Wi-Fi access points with the hardened case for outdoor deployments used in many industrial contexts. Though its wireless access strategy is firmed rooted in the Wi-Fi ecosystem, it takes a technology-agnostic view when it comes to engaging in large strategic accounts. It works closely with many industrial automation players.

COMBA

Comba holds a strong position in supporting coverage solutions in China, as well as a few South Asian and Latin American markets. The company supplies a wide range of repeaters, DAS radio heads, TMAs, residential and indoor small cells, and other coverage related products. The company's DAS solution with high-gain antennas has been used in several railway applications including the Beijing-Tianjin Intercity Rail and the Qinghai-Tibet railroad as well as tunnel coverage applications in Hong Kong, Singapore, Thailand and Latin America. The company also offers TETRA public safety solutions.

CRADLEPOINT

Based in Boise, Idaho, Cradlepoint provides cloud-based LTE networking solutions for distributed enterprises. The company's software-defined NetCloud platform packaged with ruggedized LTE mobile routers offer branch and IoT networking solutions for police and first responder vehicles, utility service trucks, or in environments where reliable wireless connectivity is needed.

DRUID SOFTWARE

Druid is a software development company based in Ireland that provides cellular core applications to system integrators, OEMs and channel distributors. The company's core software applications have been adopted in several vertical segments including public utilities, healthcare, transportation, manufacturing, and public safety. The company targets its core software solution in enterprise communications, cellular IoT, mobile edge computing, and public safety.

EMERSON

Emerson is a major industrial automation company with a focus on electrical equipment. The company offers a broad portfolio of wired and wireless communication gears for industrial use. Based in St. Louis, it has a big presence and market share in the USA. Like

others, it provides numerous instrumentation sensors for industrial automation and offers communications network and instrumentation under its Rosemount brand.

Ericsson

Ericsson has deployed several large Private LTE systems in multiple sectors including LTE base stations for TampNet in the Gulf of Mexico to connect offshore oil rigs combined with microwave for backhaul transport; LTE in an underground mine in Canada with Ambra; LTE for port automation at Rotterdam; and LTE network deployment at Southern Linc Wireless to replace iDEN system for utility network and also to support regional mobile service. The company has several Industrie 4.0 reference factories to the trial 5G application in smart factory automation.

Freewave

Freewave is a small company based in Boulder that develops wireless networking equipment for industrial and military applications. Its proprietary radios support SCADA applications for oil & gas, utilities, and others. The company is positioning its 900 MHz and 2.4 GHz radio products as a low-power, long-range alternative to Wi-Fi, Bluetooth, LoRa, and Zigbee in industrial IoT applications.

Future Technologies

Future Technologies Venture, LLC is an engineering services company based in the Atlanta area. The company provides planning, design, implementation, and support services for communications solutions and offers broadband and cellular solutions. The company focuses on wireless carriers as well as vertical industries including oil and gas, railroad, utility, public safety, and government sectors.

General Dynamics Mission Systems

General Dynamics Mission Systems business unit provides communication networks, radios, and satellite technology for defense, public safety, and intelligence agencies. The company division provides LTE Cell on Wheels (COW) used in emergency and public safety applications. The technology solution provides a virtualized EPC core network, eNodeB base stations, and Band 14 outdoor user devices.

General Electric

Based in San Ramon, CA, GE Digital has put together multiple software/platform assets through acquisitions and internal product development for the wider industrial IoT digital

transformation marketplace. With the recent corporate restructuring, GE Digital is being spun off as an independent company. As a part of this corporate transaction that takes a bulk of the GE Digital business as an independent company, ServiceMax will be sold to a private equity firm, and the remaining business, likely including its Predix platform and machine analytics platform acquired from the Meridium acquisition back in 2016, will be spun off as an independent company with about $1.2B of revenue. GE offers a portfolio of WiMAX and cellular wireless products for industrial communications networks. Its MDS radios had been deployed in smart metering applications at CenterPoint Energy in the Houston area.

HUAWEI

Huawei has been engaged with many Private LTE projects mainly in China and other regions around the world. The company offers LTE solutions under "enterprise LTE" (eLTE) brand for applications in railway (GSM-R and LTE-R) and Public Safety LTE launches in several major cities in China. More recently, it has been engaged on several smart grid, smart city, utility, and airport projects. With a full suite of wireless and fixed infrastructure, the company is well positioned especially in China and in markets where it has a strong presence with operators.

INNOVATIVE WIRELESS TECHNOLOGIES

Virginia-based IWT has a long history of offering different wireless solutions to industrial customers from Bluetooth to private mobile radio systems. Its SENTINEL is an ad-hoc wireless network for communications and tracking. The wireless mesh nodes act like repeaters and are used in underground mines. The company's RFID reverse tracking system is used in mine rescue purposes and has become the standard for US Federal and State mine rescue teams.

IP.ACCESS

ip.access has a long history in the small cells industry with early femtocell wins at AT&T and T-Mobile and a few other mobile operators. The company has expanded its market focus towards Private LTE on the shared spectrum and the government sector with security and surveillance products. Also, the company is expanding into other Private LTE sectors in transportation and rural outdoor applications.

KUKA

Based in Germany, KUKA is one of the leading manufacturers of industrial robots. The company offers robots for automotive and electronics precision assembly. The company is

active in the Industrie 4.0 initiative in the exploration of 5G use cases in smart factory applications which will undoubtedly involve its industrial robots.

LEMKO

Based in Schaumburg, Illinois, Lemko is primarily a software company that offers virtualized packet core networks. The company is targeting its packet core software along with CBRS radios to target private LTE applications in agriculture and other sectors. The company is working with its customers to deploy private LTE on 3.65 GHz band using its EZ LTE solution.

LUMINATE WIRELESS

Based in Silicon Valley, Luminate Wireless is a VC-backed company that provides Private LTE infrastructure as a service for enterprise connectivity. The company's solution suite is comprised of Luminate Mobile Cloud (virtualized Core), Insight network management system (network management), and Luminate Enterprise Access Points (radios). The Luminate Mobile Cloud delivers 3GPP virtual network functions (VNFs) in a web-scale distributed system, and the radio access points are PoE-powered LTE devices that are deployed and managed like Wi-Fi through its Mobile Cloud and Insight management system.

MAVENIR

Mavenir, based in Richardson, Texas, provides virtualized 5G core and IMS solutions along with enterprise LTE radios. The company has been an active participant in the "open RAN" movement. Along with Altiostar and Parallel Wireless, the company was selected for pilot OpenRAN deployments with Telefonica and Vodafone. In addition, the company announced its Open RAN partner ecosystem comprised of NEC, Baicells, MTI, Tecore Networks, AceAxis, KMW, Benetel, Commscope, Blue Danube Systems, and Airrays.

MOTOROLA SOLUTIONS

Motorola Solutions is a global leader in Public Safety systems. With a dominant market share in Public Safety systems including terminals and LMR radios, the company offers a full suite of legacy TETRA, P25 systems and PS-LTE terminals for FirstNet. While not a big player in infrastructure now, it is a dominant player in the Public Safety terminals market.

NEC AUSTRALIA

NEC Australia offers a complete Private LTE solution comprised of fully owned or managed cloud EPC and FDD and TDD LTE radios targeting multiple vertical sectors including government and industries. The outdoor LTE radios range in power from 1W to 10W across

multiple spectrum bands including 1.8 GHz, 2.6 GHz for FDD and bands 40, 41, 42, 43, and other C-bands around 3.5 GHz for TDD.

NetNumber

Headquartered in Boston, NetNumber provides virtualized EPC solutions to the Private LTE market. The company's TITAN platform enables signaling core for specific enterprise use cases and can run on compact commercial off-the-shelf servers. For a private broadband application, the TITAN platform can support HSS, PCRF, and Serving Gateway functions. In addition, the platform can support CSCF, AAA, and BGCF functions related to IMS services. The company's Private LTE solutions have been deployed in public safety application in Europe and in mining.

Nokia

Nokia is taking a big step towards Private LTE announcing a separate business unit that focuses on the Enterprise segment besides the traditional operators. With a full slate of IP/optical, fixed, wireless, Core, Software, and Services, the company's entire suite of offerings can be brought to bear in the Private LTE segment especially as they engage with very large industrial automation players like Siemens, ABB, etc. The company is working with several large industry players to foster the Private LTE ecosystem.

Parallel Wireless

Parallel Wireless has introduced several solution offerings targeted at different segments of the market. It has launched its distributed small cell architecture solution based on HetNet Gateway to ease the deployment of LTE infrastructure. The company is well known for deployments in "unconnected" regions using high-power and mid-power small cells in rural/remote applications in Africa, UK, Australia, and the US. The company has also deployed public safety and military LTE infrastructure in fixed and nomadic settings.

pdvWireless

PdVWireless bought Sprint's 900MHz spectrum previously used in Nextel's iDEN network. The company's 900MHz spectrum holding (896-901 / 935-940 MHz) is currently assigned in 12.5 kHz bandwidth increments. The company is seeking to reassign the bandwidth into wider channels for both narrowband and broadband operations using LTE for private LTE applications.

QUORTUS

Based in the UK, Quortus provides virtualized mobile core solutions with a focus on edge computing. The company has partnered with Fujitsu to deploy Quortus ECX Enterprise and a range of core products as part of Fujitsu's comprehensive range of Private LTE solutions for enterprises in Japan and is partnering with Airspan in the AutoAir initiative to bring together the UK's 5G and automotive players.

RADWIN

Based in Israel, Radwin provides a full suite of point-to-point and point-to-multipoint wireless solutions for municipalities and industries. Under the product branding of "JET" series, the company offers 5 GHz and 3.5 GHz radio gears. In addition to the fixed wireless access market, the company is positioning its JET products for multiple industrial segments including Utilities, Smart City and IoT applications to broaden the market appeal.

RAJANT

Rajant is a small company based in PA near Philadelphia that offers Wi-Fi mesh networking solutions that are used in "open pit" mines. The company's proprietary meshing architecture uses the "multiple radio node to multiple radio node" design, so there are always multiple paths to connect providing resiliency to faults. The company's meshing solution is favored in small mines the solution can enable communication with limited infrastructure deployment to get started.

REDLINE COMMUNICATIONS

Based in Canada, Redline has long served energy and other industrial sectors with its wide-area wireless network equipment. Redline networks are used by oil and gas companies to manage onshore and offshore assets, by militaries for secure battlefield communications, by municipalities to remotely monitor infrastructure, and by telecom service providers to deliver premium services. In addition to its proprietary solution, the company has developed an LTE-based system.

RUCKUS WIRELESS

Ruckus Wireless runs as a wholly-owned subsidiary of ARRIS. (ARRIS is in the process of being acquired by Commscope.) The company uses adaptive antenna technology to differentiate its carrier-class Wi-Fi access points. More recently, the company announced its CBRS small cell product portfolio. Combined with Commscope and its SAS business under

ComSearch, the company can offer a complete solution from radio to cloud services to Private LTE users.

SAMSUNG NETWORKS

Samsung Networks is one of the early movers in 5G. Besides its successes in RAN deployments at Jio and at Verizon, the company has been picked as a network supplier for Korea Public Safety LTE system. With its Small Cell and virtualized EPC product portfolio, the company can theoretically offer a complete solution for Private LTE. Establishing channel partnerships with key industrial players would be required to effectively target industrial automation opportunities.

SANDVIK

Sandvik is a global engineering company based in Sweden. The company develops tools and tooling systems for industrial metal cutting, mining, and construction industries. Sandvik Mining and Rock Technology division within the company is working with Nokia to develop solutions for Private LTE and 5G technology for the mining industry. Nokia Digital Automation Cloud platform which offers connectivity enabling advanced applications will be tested in the Sandvik test mine in Tampere, Finland.

SCHNEIDER ELECTRIC

Schneider Electric is a multinational corporation based in France and specializes in energy management. It provides a complete solution offering ranging from hardware to software and services. It provides diverse hardware solutions ranging from screws to robots.

SIEMENS

Siemens is one of the leading solutions providers in industrial automation. It has a long history of serving many key industries including Oil & Gas, Utilities, Manufacturing, etc. with broad hardware, software, and services portfolio. In industrial communications space, it offers a multitude of products supporting the key Industrial Ethernet protocols including PROFIBUS, PROFINET, EtherNet/IP, etc. In wireless communications, it offers WiMAX products under its RuggedCom brand and industrial Wi-Fi products under the SCALANCE brand. The company also offers 4G LTE solution under its RuggedCom WIN brand. Its products are known for deployments in harsh environments such as offshore oil fields and mines. It has a strong presence in Utilities and many other sectors.

SPIDERCLOUD

Now as a business group within Corning, SpiderCloud offers a range of enterprise small cell solutions including licensed LTE, CBRS, LTE-U/LAA, and MulteFire. The company is focused on enterprise networks, using a centralized controller to coordinate both Wi-Fi and licensed/unlicensed/shared LTE radio nodes. The company has established a key partnership with Cisco, where they work together to outfit the Cisco Wi-Fi APs in the field with "plug-in" modules, and also where Cisco sells the SpiderCloud solution for enterprise opportunities. With a long history of providing indoor LTE solutions in the enterprise space, the company is positioned to offer Private LTE radios for different vertical segments.

STAR SOLUTIONS

Based in Canada, Star Solutions offer LTE network solutions to mobile operators, private network operators for industries, and public safety organizations deploying emergency networks. The company's solution is comprised of Sonata EPC core and LTE radios. The company has deployed network systems in over 30 countries to operators, government agencies, military, mines, police, and other public safety groups. The company recently joined the CBRS Alliance in January 2019.

TAIT COMMUNICATIONS

Tait Communications is a New Zealand based company developing public safety P25 radio products. The company built 800 MHz private LTE network for a Utility in New Zealand a few years back. The company has a hardware solution that allows public safety personnel to automatically access the best network from a choice of private LTE network, public LTE network, and narrowband LMR system.

TAMPNET

Tampnet operates the largest offshore communications network in the North Sea and the Gulf of Mexico. The company provides network infrastructure services to more than 350 Oil & Gas platforms and rigs. The company has undersea fiber network as well as LTE networks comprised of mostly macro base stations.

TELRAD

Telrad offers LTE gear for mainly for wireless ISPs in the 2.5 and 3.5 GHz band. It has recently signed an agreement with Federated Wireless to extend the operation of its LTE gears in the CBRS bands. The company touts software-defined radio capabilities from its Alvarion acquisition. The wider Telrad parent company based in Israel has other businesses related to

telecom. Some of its network gears are used in industrial applications where a broad coverage and capacity are sought.

UKKOVERKOT

Ukkoverkot is a Finnish private network operator. The company has some spectrum ownership in Finland and is working with Nokia to build Private LTE networks across Finland including for the airport operator Finavia, Port of HaminaKotka, crane manufacturer Konecranes, and Sandvik for mining.

URSYS

Ursys is an Australia based company that provides satellite-based voice and data communications for enterprise applications. The company provides Private LTE networks for remote site engineering projects and remote communities. The company can provide LTE systems for up to 2000 subscribers as a managed service, using satellite or terrestrial backhaul. The company is trialing two LTE site deployments for the "smart farm" application providing an LTE coverage in a remote farming community. The network is utilizing satellite backhaul from Optus.

YOKOGAWA

Yokogawa is a Japanese company with businesses in measure and control systems and IT solutions. The company is known for its flow meters, oxygen analyzers, and automatic control systems used in process industries like Oil & Gas, Chemical, Water Utility, etc. It provides ISA 100 compliant pressure, temperature transmitters.

ZINWAVE

Zinwave is a Dallas-based company focused on providing in-building cellular coverage solution for the enterprise. Zinwave provides a turnkey solution which includes: professional services including design, project management, and installation; the RF source; DAS solution covering public safety, cellular and CBRS bands. The company also offers so-called Cellular as a Service (CaaS)™ for funding options, and a Network Management System for system monitoring and maintenance. Zinwave's indoor solution consists of five components and supports frequencies from 150MHz to 2.7GHz on one remote hardware layer. Zinwave customers include global Fortune 100 companies and span a wide array of industries including commercial real estate, corporate campuses, healthcare, hospitality, airports, universities, public venues, casinos, and even yachts.

8 ACRONYMS

3GPP: Third Generation Partnership Project

802.1x: A security platform standard established by IEEE.

802.11: An umbrella standard which encompasses multiple unlicensed communications standards within the IEEE.

802.11ac: the current generation of the 802.11 standard widely being deployed.

802.11ax: Also known as Wi-Fi 6, this is the latest Wi-Fi broadband technology

802.11i: An IEEE security specification for Wi-Fi networks.

802.11k: An IEEE standard for radio resource management to assist in limited mobility.

802.11r: An IEEE standard for rapid transition from one AP to another.

802.11u: The IEEE standard associated with Hotspot 2.0.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

AES: Advanced Encryption Standard.

AP: Access Point (often referring to Wi-Fi access point)

ATEX: ATmosphere Explosives (European directive that describes what equipment and work space is allowed in an environment with explosive environments)

BTS: Base Transceiver Station

CA: Carrier Aggregation

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

eMTC: enhanced Machine Type Communication (also known as LTE Cat-M1)

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

gNodeB: "5G" NodeB ("next generation" NodeB - corresponds to a 5G base station)

GSM: Global System for Mobile communications, a 2G radio interface

GSM-R: GSM-Railway (protocol based on 3GPP designed for railway communication)

GTP: GPRS Tunneling Protocol

HARQ: Hybrid Automatic Repeat Request

HetNet: Heterogeneous Network

IEEE: Institute of Electrical and Electronics Engineers

IP: Internet Protocol

IPSec: Internet Protocol Security

IPv4: Internet Protocol version 4

IPv6: Internet Protocol version 6

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-R: LTE-Railway

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

MAC: Media Access Control layer

MAS: Multiple Address System (900MHz master-repeater radio system used in Utility)

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NB-IoT: Narrowband Internet of Things

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

PS-LTE: Public Safety LTE

PtMP: Point-to-MultiPoint

PtP: Point-to-Point

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SON: Self Organizing Network

sXGP: shared eXtended Global Platform (promoting TD-LTE operation in 1.9GHz PHS/DECT spectrum)

TD-LTE: Time Domain-based Long Term Evolution

TSN: Time Sensitive Networking (IEEE 802 standard initiative to define deterministic industrial Ethernet features into the global standard instead of vendor-specific implementations to foster interoperability)

TTI: Transmission Time Interval

UE: User Equipment

URLLC: Ultra Reliable Low Latency Communication (5G low-latency)

VAR: Value Added Reseller

Wi-Fi: Wireless Fidelity (802.11 data communications)

WirelessHART: Wireless Highway Addressable Remote Transducer, industrial wireless sensor networking technology for process field device networks

WLAN: Wireless Local Area Network

9 METHODOLOGY

To create estimates and forecasts for the Private LTE market, Mobile Experts relied on direct input from more than 25 industry sources, with many different mobile operators, industrial automation companies, vendors, and software solutions providers contributing to the overall analysis to give a detailed global view of the market. Mobile Experts has also spoken with more than 20 other companies in related business areas for cellular IoT business areas.

Mobile Experts built a "top-down" forecast based on direct input from mobile operators, vendors, and system integrators. Then, Mobile Experts built a "bottom-up" forecast through discussions with OEMs, automation companies, software developers, and module suppliers in the supply chain. To understand the existing private wireless market in various industries, financial disclosures, investor presentations, and earnings transcripts were used to provide a high-level view of the various industry sectors.

To determine the end device market for Private LTE, we relied on our own *Cellular IoT 2019* report (published in December 2018).